CONSTRUCTION SITE SAFETY ANALYSIS FOR HUMAN-EQUIPMENT INTERACTION USING SPATIO-TEMPORAL DATA

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CONSTRUCTION SITE SAFETY ANALYSIS FOR HUMAN-EQUIPMENT INTERACTION USING SPATIO-TEMPORAL DATA

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GLOSSARY

ACD Activity Cycle Diagram.

AEC Architecture Engineering and Construction.

ASCE American Society of Civil Engineers.

BBS Behavior Based Safety.

BLS Bureau of Labor Statistics.

CA Cellular Automata.

CEM Construction Engineering and Management.

CFOI Census of Fatal Occupational Injuries.

CII Construction Industry Institute.

CSV Comma Separated Values.

CY Cubic Yard.

CYCLONE CYClic Operations NEtwork.

DEVS Discrete-Event systems Specification.

DGPS Differential Global Positioning System.

EPU Equipment Protection Unit.

FOV Field of View.

GIS Geographic Information System.

GPS Global Positioning System.

ITCP Internal Traffic Control Plan.

JHA Job Hazard Analysis.

LiDAR Light Detection And Ranging.

LOS Light of Sight.

MEP Mechanical, Electrical and Plumbing.

NAD North American Datum.

NIOSH National Institute of Occupational Safety and Health.

OSHA Occupational Safety and Health Administration.

PDA Personal Digital Assistant.

PHI Proximity Hazard Index.

POV Point of View.

PPU Personals Protection Unit.

PSM Physiological Status Monitoring.

RADAR Radio Distancing And Ranging.

RFID Radio Frequency Identification.

RTK Real-time Kinematic.

RTLS Real-time Location System.

RTS Robotic Total Station.

SIP Seat Index Point.

STROBOSCOPE State and Resource Based Simulation of Construction Processes.

SUI System Under Investigation.

TRIR Total Recordable Injury Rate.

UTM Universal Transverse Mercator.

UWB Ultra Wideband.

WAN Wide Area Network.

WGS World Geodetic System.

WSNs Wireless Sensor Networks.

SUMMARY

The construction industry has consistently suffered the highest number of fatalities among all human involved industries over the years. Safety managers struggle to prevent injuries and fatalities by monitoring at-risk behavior exhibited by workers and equipment operators. Current methods of identifying and reporting potential hazards on site involve periodic manual inspection, which depends upon personal judgment, is prone to human error, and consumes enormous time and resources. This research presents a framework for automatic identification and analysis of potential hazards by analyzing spatio-temporal data from construction resources. The scope of the research is limited to human-equipment interactions in outdoor construction sites involving ground workers and heavy equipment. A grid-based mapping technique is developed to quantify and visualize potentially hazardous regions caused by resource interactions on a construction site. The framework is also implemented to identify resources that are exposed to potential risk based on their interaction with other resources. Cases of proximity and blind spots are considered in order to create a weight-based scoring approach for mapping hazards on site. The framework is extended to perform "what-if" safety analysis for operation planning by iterating through multiple resource configurations. The feasibility of using both real and simulated data is explored. A sophisticated data management and operation analysis platform and a cell-based simulation engine are developed to support the process. This framework can be utilized to improve on-site safety awareness, revise construction site layout plans, and evaluate the need for warning or training workers and equipment operators. It can also be used as an education and training tool to assist safety managers in making better, more effective, and safer decisions.

CHAPTER I

INTRODUCTION

This chapter introduces the status of safety in today's construction site and describes the difference between lagging and leading indicators of safety. It also emphasizes why leading indicators are important and explores the current practices of gathering leading indicators of safety. In addition,it discusses the motivation behind the research and provides a brief outline of the thesis.

1.1 Overview

Figure 1 shows an overview of work-related fatalities suffered by workers in 2011, categorized by the industry they were involved in. It indicates that a total of 751 fatalities were suffered by the construction industry in the US, which is the highest among all the human-involved industries . The average cost of of these fatalities has been reported to be around $864,000 in 2006 value [22]. The National Safety Council reported that over $10 billion was spent by the construction industry in 2008 to compensate for fatal and non-fatal injuries [91]. Nevertheless, the construction industry provided employment to 4% of the entire workforce of the United States,which was 5.8 million workers in 2013 [17]. On the other hand, technological progress is in an unprecedented stage. There is a clear need to apply our technological capabilities to prevent construction worker injuries and fatalities by leveraging the latest technological innovations at a construction site.

1.2 Construction Fatality Statistics

A detailed analysis of occupational fatalities revealed the trend of fatalities in construction industry. Construction has suffered more than twice the average number of

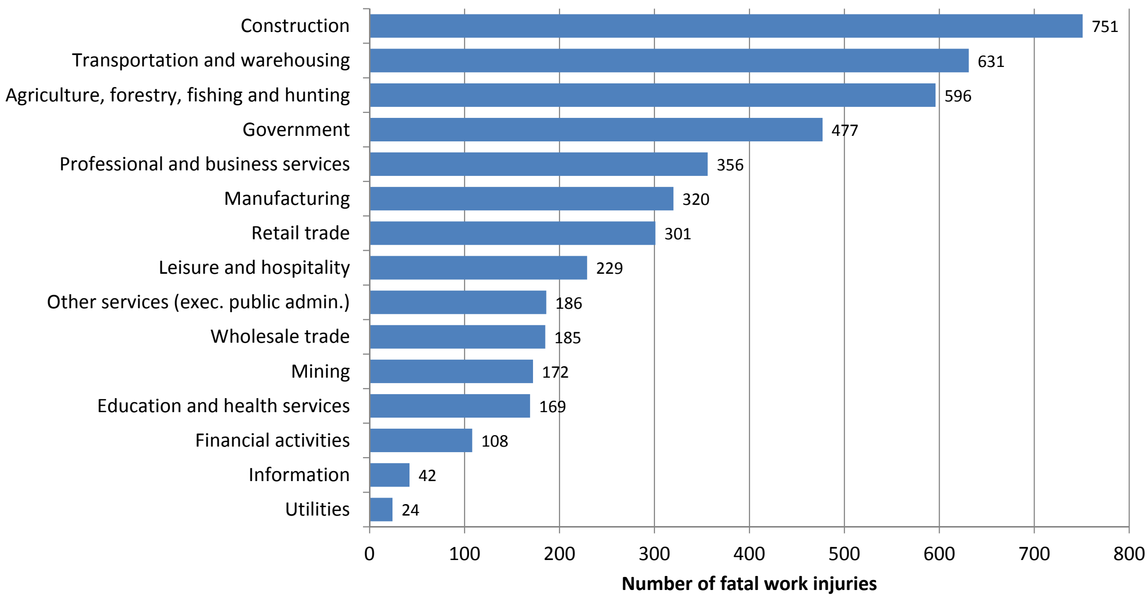


Figure 1: Overview of occupational fatalities in 2011 by industry [16].

fatalities compared to all other the industries. Figure 2 shows the historical data from 1993 to 2012 provided by the Census of Fatal Occupational Injuries (CFOI) [16]. The data were collected from multiple sources, including OSHA reports, worker's compensation reports, death certificates and media reports [99].

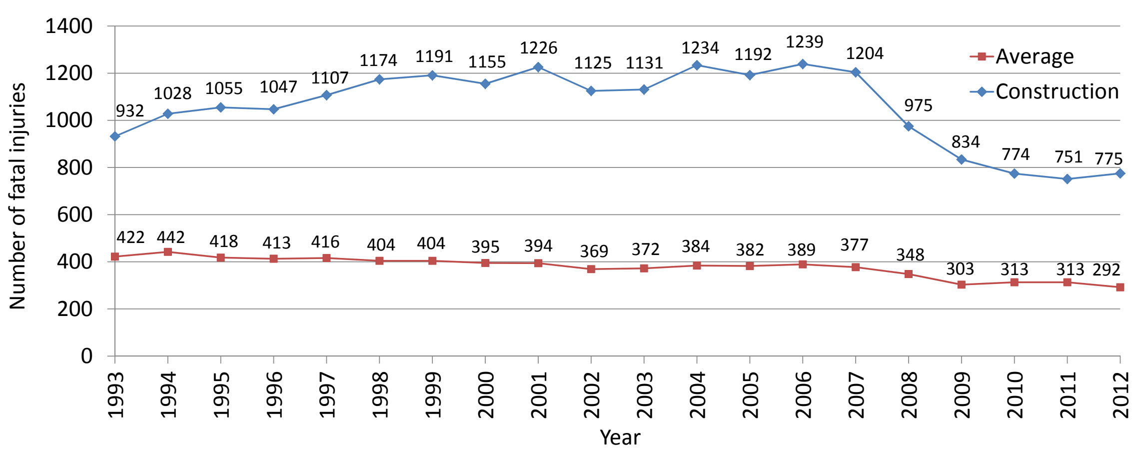


Figure 2: Overview of occupational fatalities by year [16].

The major causes of the fatalities were identified as spatio-temporal issues, which include those instances when a worker is exposed to a hazard due to his/her presence

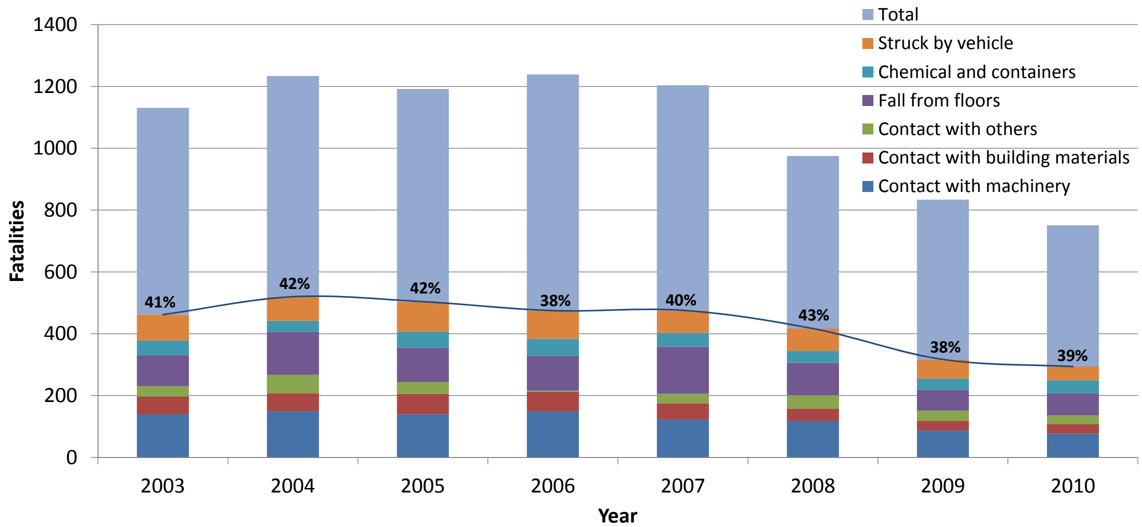


Figure 3: Overview of occupational fatalities due to spatio-temporal reasons [16].

at a particular location at a particular time. The primary cause of such events can be considered a lack of situational awareness. Situational awareness refers to one's perception of environmental elements with respect to time. In such cases. the the cause of injuries is the inability to recognize the hazard. Examples of spatio-temporal issues are coming in contact with objects (machinery, building materials and others), falls from floors, exposure to chemicals. and being struck by moving equipment or a vehicle. Ground workers performing their duties in proximity to heavy equipment were specially prone to such spatio-temporal issues [117]. Spatio-temporal issues alone claimed over 600 lives from 2004 to 2006 [113].The distribution of fatalities in these categories is shown in Figure 3, which reveals that more than one third of all the fatalities occurred as a result of spatio-temporal reasons. Figure 3 also implies that time and location are key factors that can govern the potential of a hazard on any worker on the construction site.

1.3 Non-fatal Injuries

While fatalities are of prime concern, non-fatal injuries should also be avoided. The construction industry faces significantly more non-fatal injuries than fatalities. Table

Table 1: Non-fatal injuries occurred in construction industry [15].

Year	**Total**
2012	179,100
2011	184,700
1992-2010	3,153,701

1 shows the number of non-fatal injuries that occurred in the construction industry as published by the Bureau of Labor Statistics (BLS) [15]. The reported injuries are those instances in which the worker needed to be absent from work due to the injury based on Occupational Safety and Health Administration (OSHA) standards. The statistics indicate that, in 2012, around 179,100 injuries were recorded, which accounted for 6% of the total non-fatal injuries that occurred in the private industries in the U.S. The 184,700 injuries that occurred in 2011 accounted for 8.6% of total non-fatal injuries. On average from 1992-2010, 10.6% of all injuries were in construction sector .

A formalized way of keeping track of non-fatal injuries is the Total Recordable Incidence Rate (TRIR) used by BLS . TRIR can be computed as follows:

$$TRIR = \frac{Number\ of\ OSHA\ recordable\ cases \times 200,000}{Number\ of\ employee\ labor\ hours}$$

The number 200,000 is equivalent to 100 workers working 40 hours a week for 50 weeks a year, i.e., $100 \times 40 \times 50$ hrs [18] i.e; 100 worker-exposure years . An analysis of the construction industry's TRIR shows that OSHA recordable injuries are gradually decreasing despite an increase in work-hours (Figure 4). However, a safe site with zero injuries is still far from reality. As Figure 4 also shows that the TRIR record of industries affiliated with the Construction Industry Institute (CII) had significantly lower TRIR values compared to those of the industry's average.

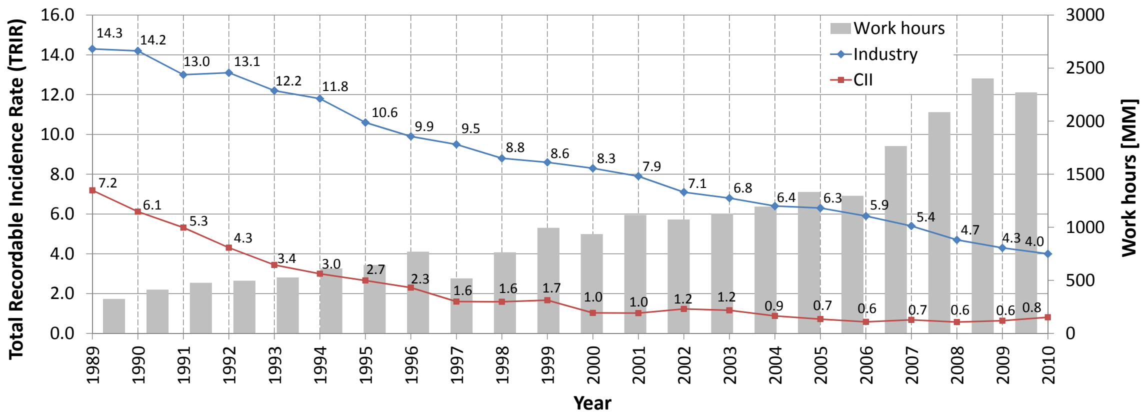


Figure 4: TRIR records of construction industry compared to members of CII [33].

Heinrichs triangle [97] in Figure 5 shows that a fatality usually comes after a succession of multiple non-fatal injuries. Similarly, one non-fatal injury is a successor of multiple first-aid injuries . Although these are problems, if looked at from different perspectives, these can serve as opportunities for safety managers to learn from. Incidents producing first-aid injuries can be studied to avoid non-fatal injuries in the future. Similarly, incidents producing non-fatal injuries can be analyzed to avoid fatalities on site. In this way, these incidents provide a safety manager multiple opportunities to learn and prevent bigger problems.

The analysis of historical data of fatalities and non-fatal injuries in Figure 2 and Table 1 demonstrate a similar trend. The triangle has been expanded in Figure 5 to accommodate near misses and at-risk behaviors. Near misses are unplanned events that had the potential to result in damage, injury or illness but did not [82]. At-risk behaviors are those behaviors that can potentially lead to a hazardous situation for a worker or equipment operator.

It should be noted that fatalities, non-fatal injuries, and first-aid injuries have a cost and a severity associated with them. These incidents are recorded and compensations are issued based on the severity of the damage. On the other hand, near misses and at-risk behaviors do not cause direct damage and may be overlooked. These

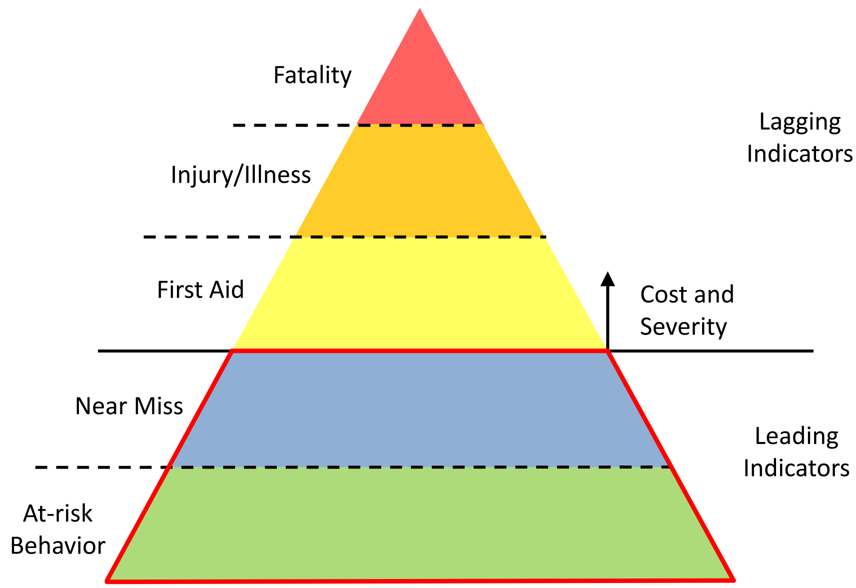


Figure 5: Modified Heinrich's triangle (based on [97]).

behaviors also do not come with direct cost or severity associated with them because no injury or damage occurs. These incidents can be utilized as multiple opportunities for safety managers to identify potential hazards on site and avoid incidents involving cost and severity. If such incidents are identified in time and preventive measures are taken, a zero injury job-site is possible.

The idea of learning from incidents that have not actually incurred any cost or severity in order to avoid potential hazards is described in detail in the next section.

1.4 Lagging and Leading Safety Indicators

The statistics on fatal and non-fatal injuries discussed in Chapter 1.3 can accurately reflect the safety performance of the site in the past but fail to assist in preventing any future injuries. The historical injury and fatality data only quantify the consequence of the event, but it can not reveal the potential for recurrence of such incidents or the context in which incidents occur [122]. Indicators that can do this are categorized as Lagging (or Downstream or Trailing or Historical or Negative) indicators. Lagging indicators change or reflect the changes only after the situation on the site has changed as a result of an undesired incident. Lagging indicators also fail to contain a systematic and pro-active measure for ongoing site safety performance. Data are collected by manual observations, and a sampling method is adapted instead of continuous data collection. Because of the manual method of data collection [64], judgment remains subjective and depends upon the level of experience and amount of observation time of the observer [119]. The amount of time spent on observation, the experience of the observer, and area of observation can heavily influence the report submitted by the observer. Knowledge about the causation and potential of recurrence of similar instances cannot be easily extracted from such indicators because of the absence of real-time data collection [46]. Lagging indicators have a long history of use on a site and, as a result, are accepted as standards in an organization [7]. Lagging indicators accurately identify past safety performance trends and are good for self comparison . Lagging indicators are easy to document and calculate. Despite having their own application [77] [65], lagging indicators focus more on the negative aspects of the site, and the data are generated only when an incident takes place on the job site [64], which is not desirable in the first place.

Better performance indicators that can precede the undesired incidents and a responsive measurement methodology can change the inability of the construction industry to minimize or eliminate injuries from the site [59] [37]. Leading (or Upstream or Predictive or Heading or Positive) indicators are those indicators that can precede an undesired event and that can help predict such events [51]. These indicators are focused primarily on the individual level of analysis instead of on the organization level, as is the case with lagging indicators [51]. Leading indicators should also be able to assist with assessing if the hazard is under control, measuring the potential severity of an event, and identifying the cause of the event [80]. Leading indicators can be used to change the criteria of severity and make modifications to the plans before they are implemented at the site [67]. Leading indicators emphasize monitoring rather than reporting the end result after the occurrence of an event [67]. Requirements for such a monitoring process include a defined information gathering mechanism, a data processing tool, and a repository for data storage and retrieval [36]. After such a monitoring mechanism is developed, the leading indicator data should ideally possess qualities like ease in understanding, numeric value, objective, credible, indicative of need for action and deviation from expectation and manipulated in relation to other indicators [67] [55]. Current practices of the implementation of leading indicators of safety in todays construction sites are introduced in Section 1.5 [4] [3].

1.5 Existing Approaches for Leading Safety Indicators

The following approaches for gathering leading indicators of safety are currently implemented in the construction industry as listed in Cheng et al. [26]

- **Safety Audits**

  A safety audit is an assessment of the presence of safety performance indicators in an organization [74]. A safety audit can be influenced by an organization's safety culture [48] and includes provision for improvements depending upon the extent to which the organizational policies are followed at a site. Periodic safety audits that analyze and report safety incidents and conditions are viewed as a measure of a leading indicator of safety.

- **Safety Training**

  Safety training considers training as a key factor for safe construction sites [3]. For comparison purposes , in this method the number of attendees, attendance records and number of employees capable of performing a desired task after training are taken into account. Different training methods using emerging technologies have also been explored lately [116]. More safety training implies greater attention to safety procedures and safer behavior.

- **Worker Safety Perception Survey**

  In a worker safety perception survey , periodic surveys are conducted to understand the the employees perception of safety [63]. The relationship between the organizational culture and the workers perceptions is also studied [96]. Also studied in this survey is the effectiveness of managerial efforts on the workers perception . It is important that the workers feel safe in order for any safety plan to be successful. Worker safety perception surveys measure the effectiveness of any safety plan from the workers perspective instead from the managerial perspective.

- **Behavior Based Safety (BBS)**

  In a behavior based safety ,manual observations are carried out over a specific period of time, and the frequency of any observed at-risk behavior is noted. The report forms a basis for future safety planning [32] [44]. An observer (or safety manager) visits the site periodically. He/she observes a part of the site for a constant amount of time (usually 2 minutes) and notes the number and type of unsafe activities that he/she observes. The activities are categorized according to the type of work happening at the site. The summary of such repetitive observations is taken as the basis for future safety planning.

- **Job Hazard Analysis (JHA)**

  A job hazard analysis identifies the steps involved in an activity and any associated hazards [106]. From the resulting list, hazard control plans and safety procedures to be followed are developed. This analysis serves as an on-site risk assessment technique [94]. Multiple potential hazards can be associated with each task performed by a worker on a site. Knowledge of such hazards and their mitigation measures depend upon the experience of the worker in similar tasks in the past. Job hazard analysis is a way of identifying potential hazards before starting the activity and training the worker to avoid those hazards. JHA informs the worker about all foreseeable hazards and prepares him/her to be prepared in case any such hazards appear on the site where the work is being performed.

- **Near Miss Reporting**

  Near miss reporting documents and report near misses and utilizes this information so that managers or workers can take preventive measures in the future. Methods for data collection, reporting, and analysis have been proposed by many researchers and successfully implemented in multiple companies [81] [20]. Near miss reporting includes details about the incident, including the cause, if possible. A near miss can be subjective and requirements for reporting can vary from task to task or company to company. Near miss reports are later studied to avoid repetition of such cases at the site.

1.6 Major Spatio-temporal Issues

Several spatio-temporal issues can be responsible for potential hazards on a construction site. Blind spots, proximity, the velocity of equipment, the type of equipment, the time of day, and the area of the site can be some of the spatio-temporal issues, based on studies on past fatalities on construction sites [68] [66] [61]. The types of spatio-temporal issues are revisited in Chapter 6. Exposing workers to dangerous spatio-temporal conditions is considered at-risk behavior . This research studies two major spatio-temporal issues: blind spots and proximity.

1.6.1 Blind spot

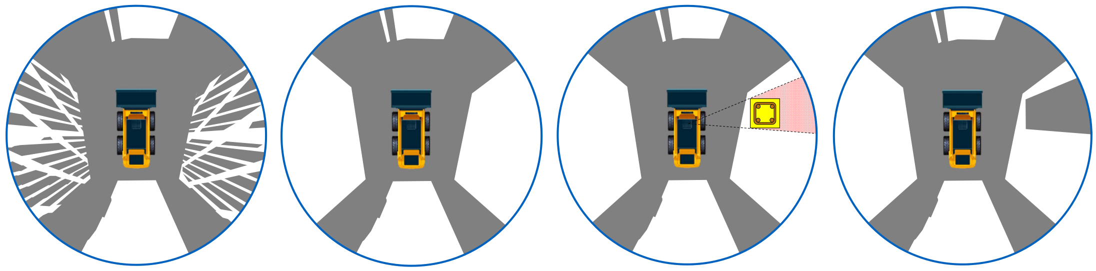
The regions around a piece of equipment not visible to the equipment operator are called blindspots [103]. It has been found that 75% of all struck-by fatalities are caused by visibility-related issues [68]. The blind spots of equipment can be measured using manual or computer simulation methods [12] (shown in Figure 6). The manual approach involves placing an artificial light at the operator's Point of View (POV) with the help of a Seat Index Point (SIP) apparatus. Then, a visibility of test screen is measured [11]. Another method developed by The National Institute of Occupational Safety and Health (NIOSH) involves marking polar-grids manually for the area that is visible from the centrally located operator's seat [89]. Computer Aided Design (CAD) models were used for a computer simulation method to create a blind spot diagram by utilizing artificial lighting [90]. A three dimensional point cloud from a laser scanner has been applied recently to automatically generate and validate blind spot regions around the equipment [114] [83] [103]. The blind spot measurements were done on the ground level within a 12 m radius around the operator's POV according to NIOSH's standard.

The limitations of such blind spots were also pointed out by Ray [104]. These methods assumed a monocular vision model and most of them did not incorporate indirect visibility through mirrors. A method developed by Ray [104] was capable of computing volumetric blind spots and measure the dynamic visibility of the operator by tracking his/her head. However, the change in Field of View (FOV) from the operator's eye movement, the articulation in the equipment, or presence of a load and moving parts were not addressed.

The blind spot diagram used in this research was obtained from Hefner and Breen [60], Marks et al. [83] and Ray and Teizer [103]. Figure 6 shows the process of measuring blind spot for moving equipment.

1.6.2 Proximity

Proximity is defined as nearness in space, time, or relationship [82]. As discussed in Chapter 1, struck-by incidents between equipment and workers contribute to the



(a) (b) (c) (d)

Figure 6: Blindspot map analysis for each instance (a) Actual blindspot, (b) Simplified blindspot, (c) Simplified blindspot with occlusion, (d) Resultant blindspot map

majority of construction accidents. Figure 7 shows designation of blindspot and proximity zones around an equipment. Proximity hazards also contribute to a lack of situational awareness [82]. Real-time alert systems for proximity have been proved to be the most effective way to avoid these hazards. Although the focus of this research is not to deliver real-time alerts, but rather to gather proximity related information from the site, some background on the current status of proximity alert systems is presented. Radio Frequency based proximity detection and alert systems can provide some warning to the equipment operator and worker in real-time [84]. These devices required equipment protection units (EPUs) on the equipment and workers needed to be equipped with personal protection units (PPUs). A technology that is heavily deployed in mining industry is a mesh radio system with equipment acting as nodes to form a dynamic interconnected system to keep track of distance between objects [1]. Radio distancing and ranging (RADAR) based and magnetic marking field based devices work with similar requirements with units installed on all the entities [120] [107]. Vision-based technologies were also explored that did not need tagging of the entities using stereo vision approaches [128]. However, these technologies have not been able to detect and record the location of the incident, which is something that is required for future planning. A micro-level analysis of proximity specific problems was done in to determine pro-active measures for safety [26]. The location of such incidents were also highlighted [28].

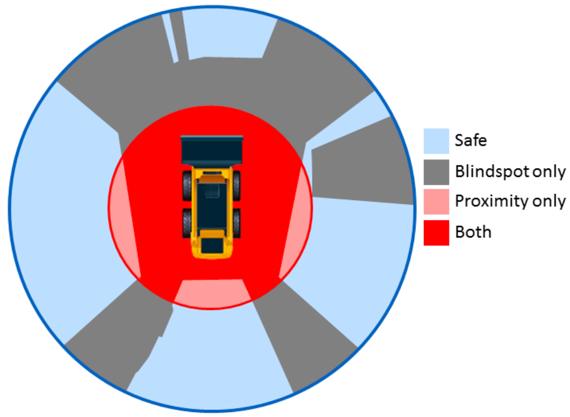


Figure 7: Categorization of zones based on potential hazard.

1.7 Motivation

Figure 4 shows the difference in TRIR records for the overall construction industry compared to the industries in CII. Figure 4 also implies that a much lower injury rate is feasible at today's construction sites by following best practices [34] and prioritizing safety at the site.

The construction industry is in need of preventive measures for safety rather than mere knowledge of what has already happened on the site. Emerging technologies provide a promising basis for gathering the required information from the site and analyzing the data to mine valuable information that can help better understand and deal with safety related issues. As demonstrated in Figure 8, several barriers can prevent a worker from being exposed to a hazard. Failure of these barriers can eventually lead to an undesired event. Management and manual observation methods randomly sample the working environment and worker's behavior on site. This method of sampling is not exhaustive and leaves "holes" (situations in which workers can be exposed to hazards) as shown in "the Swiss Cheese Model" in Figure 8. Each preventive hierarchy implemented on site introduces one more layer towards the workers safety. The swiss-cheese model also envisions chances of failure or absence of these barriers that keeps the possibility of hazard alive. Figure 8 shows that an injury

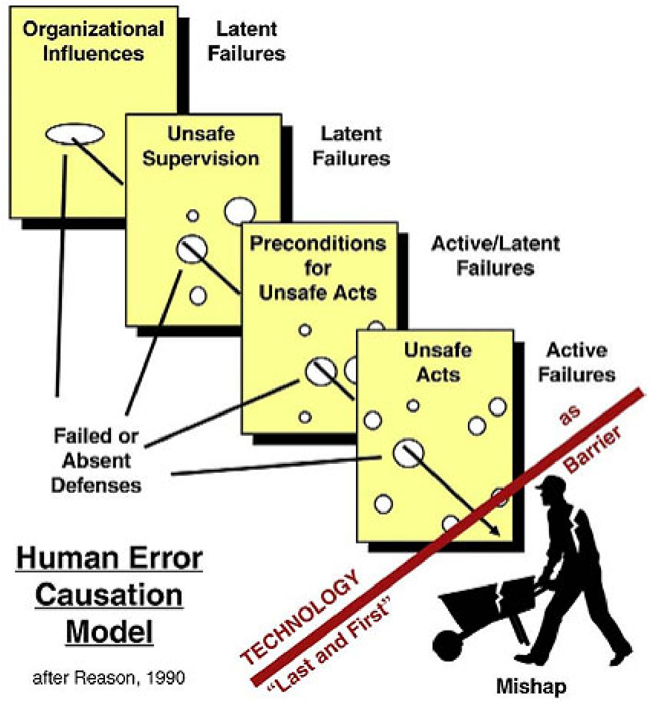


Figure 8: Human error causation model with technology as an extra barrier [113].

is the result of simultaneous occurrence of unsafe organizational influences, unsafe supervision, preconditions for unsafe acts, and unsafe acts themselves. Because a hazard remains unnoticed in all these different barriers, a worker becomes exposed to it. However, technology can act as a new kind of barrier to warn about such failures. It can detect the absence of such barriers in real-time (see the holes in the cheese) to prevent any undesired incidents or collect data regarding such incidents that can be used as a reference in the future. Technology can be deployed to collect data and monitor and evaluate the site continuously.

This study is motivated by the fact that there is now the potential to enhance safety on a construction site by identifying potential hazards based on the at-risk behavior of the resources. Such behavior can also be used as learning opportunities for future planning and decision making. Lastly, emerging technologies have potential to gather relevant data and act as a barrier to prevent injuries at site.

1.8 Thesis Outline

This thesis provides a framework for developing a formalized approach towards construction site safety analysis using spatio-temporal data from construction resources fused with information regarding site geometry. The thesis is divided into chapters by categorizing the different aspects of construction that come together to form the overall framework into different chapters. Following is a brief description of the contents of the chapters.

- **Chapter 1** provides an overview of safety situations in the construction industry and summarizes the current practices being implemented to prevent undesirable incidents at sites. It identifies fatalities and injuries at construction sites as problems and discusses a need for continuous site monitoring by leveraging emerging technologies .

- **Chapter 2** presents the research framework and includes the research questions and hypothesis that form the backbone of this research. I lists the major objectives of the research And discusses the scope and limitations of the research.

- **Chapter 3** describes the sources of spatio-temporal data and the technology selection process and also presents a detailed description of experiments performed in sites and lab environments. It also discusses data management and the significance of different data sources.

- **Chapter 4** demonstrates the method of utilizing spatio-temporal data for construction site operation analysis to better understand the operations happening on the site. It presents zone and speed analysis and presents an analysis of cyclic activities and proximity events analysis as key for site operation analysis.

- **Chapter 5** outlines the process for developing a cell-based simulation engine and simulation model for an earthmoving operation. It shows how results from construction site operation analysis can be used for simulation. It concludes by discussing the potential of site safety analysis using simulated data.

- **Chapter 6** presents the process of using spatio-temporal data for identifying and quantifying potential hazards at a construction site. Data from different sources are used to demonstrate the feasibility of the method. The chapter finishes by demonstrating applications of the method in construction monitoring and planning related activities.

- **Chapter 7** concludes the thesis by summarizing the core concept of the thesis. It includes the contributions and impact of the research and mentions suggestions for future work.

1.9 Summary

The many pieces of equipment deployed on a construction site may increase the productivity of the site, but they also bring a potential threat for ground workers due to their continuous interaction to successfully complete the job. Chapter 1 discusses such interactions and the historical record of fatalities and injuries caused by them It was observed that for human-equipment interaction, situational awareness plays a vital role and the workers suffer fatalities or injuries because they are present at the wrong place at the wrong time. It was found that manual observation methods were not efficient at tracking such incidents. A continuous monitoring method using location tracking technology was identified as potential method for analyzing spatio-temporal interactions between ground workers and equipment on site. This research presents a method for implementing such spatial tracking technology to effectively monitor the site for any potential hazard and take preventive measures to avoid them. The chapter reviewed different technologies capable of tracking resources at a construction site and discussed their advantages and disadvantages. It then presented the results to the experiments performed at different construction sites as well as in a virtual environment to support various steps towards identifying and quantifying such potential hazards caused by spatia-temporal interactions between ground workers and equipment. The chapter concluded by identifying an automated method of analyzing site operations, incorporating spatial constraints in monitoring and planning and objectively identifying hazards.

CHAPTER II

RESEARCH OBJECTIVES AND METHODOLOGY

This chapter presents the objectives of the research. The main focus of this research is to gather data pertaining to at-risk behavior of the workers and equipment on a site. The steps to accomplish this are listed in this chapter, which also formulates the scope within which the research was conducted and outlines the limitations. The chapter next presents the hypothesis that the research tests. The later part of the chapter explains in detail the framework developed for this research. The chapter concludes by briefly introducing the various phases of research that work toward the overall goal of the research.

2.1 Research Objectives

The main objective of this research is

To objectively quantify potential hazards on a construction site, to automatically generate hazard maps, and to identify resources-at-risk by leveraging spatio-temporal data.

The objective has been fulfilled in separate parts to meet the holistic goal of the research. The chapters in this thesis are based on one of these objectives. The sub-objectives, as categorized by their functionality to meet the overall objective, can be stated as

- To investigate spatio-temporal data acquisition technologies and assess the best-fit technology to gather test data on human-equipment interaction on harsh outdoor construction sites

- To develop an automated platform for understanding the operations happening on site to assist productivity and safety analysis

- To create a cell-based engine capable of simulating spatial constraints at a construction site to perform "what-if" analysis for resource interactions in different resource configurations

- To devise a method for automatically detecting and visualizing areas on site that require more attention of a safety manager and to identify resources prone to potential hazards based on their motion behavior

Milestones towards objectives

This research formulates a framework for gathering data pertaining to at-risk behavior of workers and equipment operators on a construction site. The collected data should be processed and presented in a way that is easily readable for safety managers to grasp the necessary information at a glance. The following list provides an overview of the milestones to meet to attain the goal.

- Study the current status of construction site safety data collection and investigate the properties that a leading indicator of safety should possess

- Investigate construction fatalities and injuries caused by spatio-temporal reasons and explore the cause and type of data needed to measure and mitigate potential incidents

- Leverage real-time locating systems (RTLS) for collecting spatio-temporal data from construction resources (workers and equipment)

- Compare available RTLS sensors and scrutinize their applicability in rugged construction environment

- Examine the reliability of low-cost Global Positioning System (GPS) data loggers when deployed in a real construction site
- Collect data from multiple construction sites to test the developed framework
- Develop a platform for data management with capabilities to store all the relevant data, facilitate easy retrieval and easy interface for analysis
- Develop algorithms required to automatically analyze construction operations and generate report with valuable information about site operations
- Create a simulation engine capable of incorporating spatial properties and constraints of the site for spatio-temporal kinematic planning of operations
- Identify the parameters that govern spatio-temporal issues on site
- Formulate a method to quantify potential hazards on the site objectively
- Visualize the calculated risks using heat maps and identify resources prone to potential hazards
- Test the developed method with data from real site, from a virtual environment and from result of a simulation run
- Study the current status of construction site safety data collection and investigate the properties that a leading safety indicators should possess
- Investigate construction fatalities and injuries caused by spatio-temporal reasons and explore the causes and types of data needed to measure and mitigate potential incidents
- Leverage real-time locating systems (RTLS) to collect spatio-temporal data from construction resources (workers and equipment)

- Compare available RTLS sensors and scrutinize their applicability in rugged construction environments
- Examine the reliability of low-cost Global Positioning System (GPS) data loggers deployed at a real construction site
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- Develop algorithms required to automatically analyze construction operations and generate reports with valuable information about site operations
- Create a simulation engine capable of incorporating spatial properties and constraints of the site for spatio-temporal kinematic planning of operations
- Identify the parameters that govern spatio-temporal issues on site
- Formulate a method to quantify potential hazards on the site objectively
- Visualize the calculated risks using heat maps and identify resources prone to potential hazards
- Test the developed method with data from real sites, from a virtual environment, and from a simulation run

2.2 Scope and Limitations

Each section of the research has its own scope and limitations. These individual scopes and limitations will be discussed independently in their respective chapters. The overall research methodology is formulated with following major boundaries in mind.

- Although the cause of a hazard might involve multiple factors, only spatio-temporal factors are considered here. Only space (location) and time of occurrence have been analyzed.
- Only outdoor construction operations taking place in rugged environments involving heavy construction equipment are considered.
- The research is limited to human-equipment interaction (ground workers working in the vicinity of moving equipment).
- Two major spatio-temporal issues, namely proximity instances (Chapter 1.6.2) and an equipment operator's blind spot (Chapter 1.6.1) are prioritized. Blind spots and proximity issues on a construction site and the current status of research in the respective areas are introduced in Chapter 1.6.
- Limited by technology, the research deals with post processing of data, and the results are expected to be used for planning construction operations in the future. Planning can be for the same site on another day with same or different site layout. It can also be for another site with different requirements using the simulation engine developed for this research. Real-time analysis, alerts, and solutions are not within the scope of the research.

2.3 Research Hypotheses

This research focuses on leveraging location tracking technology to gather spatio-temporal data from construction resources (equipment and workers). The data are used to quantify potential hazards on site and to identify resources prone to hazards. Each objective mentioned in Chapter 2.1 can be tested at the end of the research to verify if it is fulfilled. For the overall framework, the following two hypotheses act as the core of the research.

1. It is feasible (technically and economically) to gather real-time location data from the resources (workers and equipment operators) that can reveal their at-risk behavior based on spatio-temporal analysis of their interaction

2. At-risk behavior can be quantified into comparable numbers to assess the safety performance of the resources, and information about potentially hazardous areas on the site can be visualized to facilitate safety managers for future safety planning

2.4 Research Methodology

The entire research has been broken down into modules to demonstrate the information flow and dependencies as one part relates to another. Figure 9 shows the basic research framework developed for this research. Each box represents a module. The arrow heading into the box represents input to the module, and the arrow heading out stands for output. The dotted lines imply that it is a repetitive process and the results are fine tuned as the iteration continues. A brief introduction of the modules can be found below. A detailed description of the modules can be found in the respective chapters referred to the text following the description of the module. This section will describe the different modules introduced in Figure 9 individually. The relation of one module with others will be explained in the description of respective modules.

2.4.1 Data collection

Data collection involves both real-time location data from the resources and information about the logistics and geometric conditions of the site. Low-cost GPS data loggers are used for spatio-temporal data collection after rigorous comparison of available sensing technologies that can be deployed in an outdoor construction site. Error analysis of selected GPS data loggers is carried out and the probable nature and

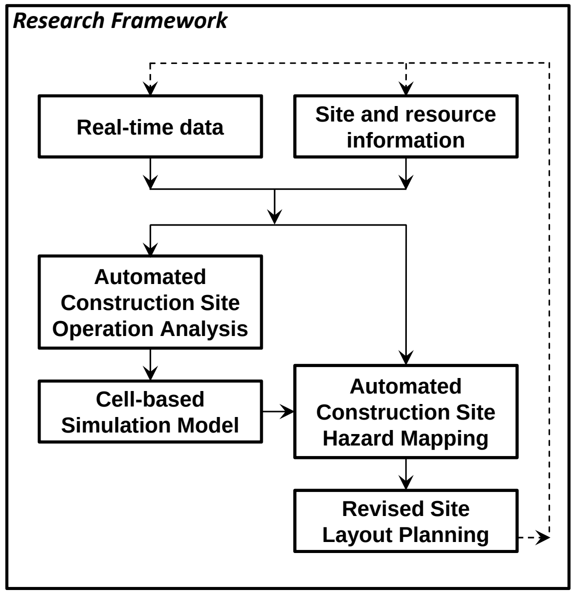


Figure 9: Developed research framework.

magnitude of error is studied. Sources of site geometry data are explored. Human generated data like site notes are also considered for data analysis. These data can be fed into an "Operation Analysis" module to understand the operations happening on the site and perform productivity-related analysis. The data can also be utilized for site safety analysis independently.

2.4.2 Operation Analysis

Operation analysis generates automatic reports of operations occurring at a site. Knowledge of the state of site operations is essential, not only for productivity analysis but also for site safety analysis. Algorithms for three major analyses are developed. Zone and speed analysis provides the time distribution of the resources in their work zones. The speed profile reveals the kinematic characteristics of the resources inside a zone. Proximity event analysis records the time of entry to user-defined proximity zone of another resource. The duration of exposure to proximity, the extent of nearness and detailed report with distances and timestamps is generated. The third analysis is the identification and analysis of cyclic activities.

2.4.3 Cell-based Simulation

Traditional construction simulation engines do not consider space directly as a constraint. However, in urban construction sites, space can be a major concern [5] and crews struggle for space while working simultaneously. To address this issue, for this research, a cell-based simulation engine based on complex systems is developed from scratch. Although spatial simulation has many benefits, it is used here to bridging result from operation analysis to safety analysis . The potential of performing "what-if" analysis for multiple resource configurations is explored. Location tracking technologies can reflect what has already happened at a site in terms of safety due to resource interaction . But, while planning for future , the interactions will depend upon the resources deployed on that day. Simulation methods can be used to create a virtual scenario with different resource configurations and study how the resources would interact if they were actually deployed on a site. Such interactions can be analyzed, and safety condition can be predicted before any plan is actually implemented on the real site.

2.4.4 Hazard mapping

Spatio-temporal risks are studied focusing on two major types of hazards, blind spots and proximity, as introduced in Chapter 1.6. A method of identifying and quantifying location-based hazards is proposed. The method involves referring to historical fatality and injury data to assess the severity of the spatio-temporal parameters and analyzing the overall potential risk for each instance of human-equipment interaction. This section introduces the parameters that involve spatio-temporal data for hazard assessment and presents the basis for the evaluation of their severity. Three sources of data are used to demonstrate the feasibility of the method, real data from a site, data from a controlled experiment, and data from a virtual environment.

CHAPTER III

TYPES OF DATA AND DATA COLLECTION

This chapter discusses the types of data that can be acquired from a construction site and the sources of such data. It presents the process of technology selection, describes tests performed on selected technology, and introduces the data collection sites and available data.

3.1 Data Sources

A construction environment consists of two distinct components. The first component is the "site" or the space where construction occurs, and the second is the resources (workers, equipment and material) that are involved in the construction process. For this research, the sources of spatio-temporal data acquired from a construction process have been categorized into two types, namely, Site Geometry and Real-time Resource Data. Each type is discussed briefly with a focus on its use in construction safety in this section.

3.1.1 Site Geometry

Site Geometry is the geometrical configuration in which the construction is taking place. The terrain of the ground, built components of the structure, site logistics, and site layout plan fall under this type. This type of data is dynamic in nature because construction is an on-going process. A member of the permanent structure can be categorized as material until it has been installed permanently at its position. For instance, a pre-fabricated beam can be classified as material until it is installed. The same beam can be termed as a component of the structure as soon as it is installed. Another example can be concrete which stays in a material laydown area as material till eventually being cast to permanently serve as a component of a structure. For this research, the site geometry is assumed to be static throughout the day. In other words, all the components of the site that do not change during the analysis period have been classified into this type. Potential sources of site geometry are briefly introduced below. In short, the components of the physical layout or final structures in the building plan yield the site geometry. However, up until the structural members are installed at their permanent place, they can be moved inside the site and can be categorized as material.

3.1.1.1 Building Information Model

A Building Information Model (BIM) integrates a computer 3D model of a building with the properties of different components, the relationships of the components with other objects in the model, and a logical classification of the objects in the model. With the use of a BIM, an accurate virtual digital model of a project can be constructed. The BIM is one of the most promising advancements in the Architecture, Engineering and Construction (AEC) industry [41] as it integrates all the aspects of the projects, structural, architectural, mechanical and electrical plumbing (MEP), and energy etc. into the same platform. It has enabled a new era of collaboration for better design and optimized performance. As the objects in a BIM hold their properties and parametric modelling can be done using these properties, the BIM can be implemented widely in fields such as estimating and scheduling etc. which have until recently been based on more or less manual techniques.

Recent studies have integrated safety into BIMs for purposes like fall protection [134] and designing temporary structures [76]. The BIM is used in this research to extract the structural components such as columns and walls that are supposed to be present on the site on the day of the experiment based on the schedule. These components act as occlusions at a site which alter the blind spot areas of the equipment operators. Temporary structures, when installed, act as temporary hazards and influence the safety conditions on site.

3.1.1.2 Laser Scan/Surveying

Laser scanners are gaining popularity because of they can capture 3D structures of the environment with a laser. Laser scanners can create a dense point cloud using a laser which is pointed as a beam while points are collected as the beam rotates horizontally or vertically [110]. Laser scanners are well-known for their fast sampling rate and millimeter-level accuracy [110]. Laser scanners are suitable for constructing as-built models of the environment and have the potential to integrate with the BIM for automatic reconstruction of facilities [111] [126]. For safety, their use has been explored in equipment operator visibility assessment [29], equipment blind spot measurement [83] [103] and excavation safety assessment [127]. Equipment operator blind spots can be used to assess the requirement of modification to the design of the equipment to minimize blind areas. The requirement of mirrors or workspace for a piece of equipment can also be analyzed using a visibility study of an equipment operator. Laser scan data are used in this research to get up-to-date information about the dimension of the excavation pit and supporting structures like shoring. In the absence of a laser scanner, as-built drawings can be created with a total station or GPS survey.

3.1.2 Real-time Data

Real-time data records the status of those entities that dynamically change during the course of data collection. Typical examples of such data are the locations of workers, equipment, or material.What is dynamic and what is not depends upon the need for data from the entity and the frequency at which data are being collected. If a site layout is being planned for a month, the location of a mobile crane might be considered dynamic. However, if data are collected for only a day and the location of the crane is fixed during the course of the analysis, the crane can be categorized as a static entity. The scope of this research is limited to spatio-temporal or location data. Various location tracking sensors have been tested on construction sites. The details, advantages and disadvantages of these technologies are discussed in Section 3.2. Other types of data mentioned in Section 3.1.3 can be used for data acquisition pertaining to various aspects of a construction activity but are fused with location data for identification and analysis of such an activity [30] [124]. Location data serve as a reference for data from other sensors and act as a context for the analysis of activities.

Although only location data is used for this research, the use of several other types of real-time data has been explored in a construction context. Workers health was monitored using Physiological Status Monitoring (PSM) devices to perform an ergonomic analysis of activities [27]. An estimation of human posture using range cameras for activity and ergonomic analysis was performed by Ray and Teizer [102]. Detailed blind spot and visibility analysis was done by tracking head poses of equipment operators [104]. Environment variables such as temperature [58], air quality [2] and rain [42] are also equally important and can affect the performance of a site.

3.1.3 Other

While the above-mentioned data types are generated by sensors and have a definitive structure in which they are collected, stored, and retrieved, a different type of data that is not structured data in a predefined pattern is predominant in the construction industry. It is believed that 70-80% of all data in any organization in 2013 was not in a structured form [69]. These data are not organized in a predefined way. They can provide information either about the site geometry or about the location of resources or both or neither. This type of data might not even be in digital format and might need specialized systems to process them. Examples of this type of data are construction documents that require natural language processing. Among various sources of unstructured data, the ones used in this research are discussed below.

3.1.3.1 Pictures/Video

Pictures and video taken at the site can give us information about both site geometry as well as resource location. Vision-based technologies can also be used to identify and track resources on a site, which is detailed in Section 3.2.4. Pictures and video can also act as a source of point cloud for 3D reconstruction of structures and for construction inspection [49] [50] [14]. If cameras are installed and calibrated for a specific site, the data generated can be used directly to acquire information without any further manual intervention. However, pictures or video taken impromptu at a site do not have any information regarding the context of the image and will require human judgment if one is to understand and acquire information from them.

3.1.3.2 Site Notes

Site notes are valuable information about human observations on site. These notes can provide information that summarizes the activities occurring on site, the experience of the observer, any special relation between entities, and details that have not been/ cannot be captured by sensors. Such data that are not generated by sensors are termed "soft data" and have been used to understand and analyze construction activities as well as to validate and improve hard data captured from sensors using data fusion methods [92] [10] [124].

3.2 Technology Comparison and Selection

A background study on sensing technologies that have the potential of being deployed in a rugged construction environment was done . The requirements for the technology to be accepted by construction industry were identified to be the following [29] [26] i The technology should be economic to deploy and maintain.

ii The data logger should be easy to install and use.

iii The technology should not require heavy infrastructure installation on the site.

iv The technology should not be limited to a specific work environment and should be scalable to any type of space.

v The size of the data loggers should be small so that they do not hamper the normal working habits of the workers.

vi The technology should work in harsh environments with moving components, variable lighting conditions, and occlusions.

vii The frequency of data logging should be one second or less. For GPS, the satellite refresh rate is 0.6 sec., so, a higher frequency rate might not yield any additional spatio-temporal information about the resources. The requirement of data logging also depends upon the velocity at which the resources move within the site.

viii The technology should work in open outdoor environments where most heavy construction takes place.

ix Depending upon the application, the technology should provide reliable and accurate measurements.

x Data transfer and processing should not require an inordinate amount of manual work and time.

xi Data collection technique should be the least invasive to privacy while meeting standards for security.

Based on these needs, the following sensing technologies were examined for their applicability.

3.2.1 Radio Frequency Identification

Radio Frequency Identification (RFID) has been used in multiple applications ranging from asset tracking and inventory management to on-site security upgrades [43] [52]. RFID tags can be active, semi-passive, or passive depending upon the power source. and the fact that their read range and lifespan vary by type [39]. RFID has also been used for indoor localization to pinpoint a location inside a facility [101]. It has also been integrated with BIM for facility management [38].

Advantages: The tags are comparatively inexpensive to use ($0.10 to $10).

Disadvantages: This technology cannot provide accurate location information unless RFID readers are heavily deployed in the field. Accuracy is a function of the density of the readers.

3.2.2 Ultra Wideband

The feasibility of deploying Ultra Wideband (UWB) systems has been explored by many researchers for tracking construction resources on a construction site [25] [117] [31] [75]. UWB is found to have a longer read range and is immune to interference caused by environmental conditions like rain and fog [25]. UWB also has higher data logging capabilities and much higher accuracy compared to RFID.

Advantages: UWB provides good location accuracy and update frequency.

Disadvantages: UWB requires heavy infrastructure installation at the site and its read range is limited only to the calibrated area and is easily affected by occlusions.

3.2.3 Global Positioning System

Global Positioning System (GPS) is another promising technology and is capable of various ranges, from expensive devices yielding millimeter level accuracy with differential correction and slow velocity to low-cost recreational devices with an accuracy of a few meters. GPS is a technology that is commercially used to track heavy equipment on site. Construction related research that has explored the use of GPS for various purposes include collision detection of construction equipment [95] and improving construction efficiency and reducing waste [78]. The application of GPS in operation analysis is discussed in Chapter 4.1.

Advantages: Lower end less accurate devices do not need site preparation for data collection. Higher end devices provide millimeter level accuracy.

Disadvantages: Higher end devices are expensive. Lower end devices suffer accuracy problems. GPS does not work indoors.

3.2.4 Vision Technologies

Unlike other sensing technologies, vision technology can track workers and equipment on site without any tags on the subjects. Stereo vision and range cameras can give three dimensional locations of the resources. Leading research in vision technology in the construction domain include vision based tracking [13], 3 dimensional tracking using on-site camera, [98], tracking for building interior construction operations [72] and human-robot integration for unstructured construction sites [45]. Marker based methods need markers to be placed on the subjects and can provide better accuracy compared to that of other vision-based methods.

Advantages: No tags are required on the subjects for camera based technologies.

Disadvantages: Vision technology is severely affected by occlusions and lighting conditions and cannot uniquely identify the subjects on site.

3.2.5 Technology for Spatial Tracking

This research specifically deals with outdoor environments and requires uniquely identifying resources despite potential occlusions on site. Especially in earthmoving operations where the site does not have any structural component and the dynamics of the site change rapidly, infrastructure installation might not be feasible in all cases. RFID, UWB, and vision-based technologies require such pre-installed infrastructure with a calibrated site. High end GPS does not require heavy infrastructure installation because it requires only a base station for a range of several kilometers, but deploying this technology is expensive, especially for tracking workers. Low-cost GPS, on the other hand, stands out as a viable solution without the requirement of any pre-installed infrastructure. It is portable , easy to install and use, and can transfer data easily.. However, low-cost GPS has been known for being less accurate than most of the technologies discussed above.

For a comparison of the analysis between equipment and equipment, the acceptable accuracy can be at the meter level because of the size of the equipment and the level of accuracy required to track the operation. For instance, an unloading activity for a dump truck does not require sub-meter accuracy for analysis purposes. The loading and unloading zones are spaces that vary depending upon the truck driver, the site configuration, and the observer who defines the zones. The size of the equipment also plays a vital role in the accuracy required to track it. Safety buffer zones can be created around the zones or equipment to make sure that the distinction between safe and unsafe zone is properly maintained. Such buffer zones can compensate for inaccuracy of the tracking technology whereas in the case of tracking workers, sub-meter accuracy might be desired for safety analysis. Since the interaction between equipment and workers is being studied, lower accuracy might not yield accurate results . In contrast, following the "Safety First" principle at a construction site, when testing a new method, it might not be wise to totally rely on technology, especially while planning for safety. The effects of technology failure should also be accounted for. One type of failure that can be easily detected is missing data points. Such a failure can be accepted as lack of data and human judgment will be required in such cases. However, for the cases in which erroneous readings are recorded by the technology, it is difficult to detect such instances and take necessary measures against them. In such situations, interpolation or filtering of data can help to some extent. Hence, a new safety planning method should be tested with a technology that exhibits such pessimistic cases , and the effect of such errors should be understood. Hence, low-cost portable GPS devices were chosen as an appropriate technology to study the feasibility of new method of site safety analysis.

3.2.6 Selected Technology

This study used commercially available Wintec G-Rays 2 data loggers (Figure 10). The dimensions of one such device are 64 x 40 x 17 mm. It weighs 55g, including the battery. With very minimal interference, if required, these units are small enough to be mounted using double sided tape anywhere on construction equipment (e.g., inside/outside the equipment cabin) and on construction workers (e.g., hard hats). Data is recorded at an update rate of 1 Hz by change in direction, motion, speed, time interval, or distance. The device starts logging data points after it acquires adequate satellite information. This typically takes a few seconds and is performed only once, at the beginning of the data collection. The device supplies continuous measurements and writes to a single data file stored on the device. It also has a push-to-log button for marking specific flag points (called push log points). This GPS data logging device is also equipped with a motion sensor to avoid recording redundant data when the device is not moving.

Figure 10: Example of a GPS data logger (Wintec G-Rays 2)

Raw output from the device can be exported in various formats. An example of some converted raw data and its attributes from a Comma Separated Values (CSV) format is shown in Table 2. The dataset then can be converted from latitude-longitude to Universal Transverse Mercator (UTM) format (Easting-Northing) for more specific data analysis and visualization purposes.

Table 2: Raw data of one GPS data logger

Order [Point no.]	Latitude [°]	Longitude [°]	Elevation [m]	Timestamp [Date and Time]	Distance from Start [km]	Distance from Last [km]	Bearing [°]	Speed [m/s]
1	33.778624	-84.395539	346	5/16/2011 6:31:37	0	0	0	0
2	33.778630	-84.395539	344	5/16/2011 6:31:38	0.001	0.001	180	2.56
3	33.778637	-84.395539	342	5/16/2011 6:31:39	0.001	0.001	180	2.56
4	33.778643	-84.395546	340	5/16/2011 6:31:40	0.002	0.001	140	3.33
5	33.778650	-84.395546	338	5/16/2011 6:31:41	0.003	0.001	180	2.56
6	33.778653	-84.395546	336	5/16/2011 6:31:42	0.003	0	180	1.28
7	33.778656	-84.395546	335	5/16/2011 6:31:43	0.004	0	180	1.28
8	33.778659	-84.395552	332	5/16/2011 6:31:44	0.004	0.001	121	2.48
9	33.778669	-84.395552	330	5/16/2011 6:31:45	0.006	0.001	180	3.84
10	33.778672	-84.395546	327	5/16/2011 6:31:46	0.006	0.001	239	2.48

3.3 Instrumental Error and Data Filtering

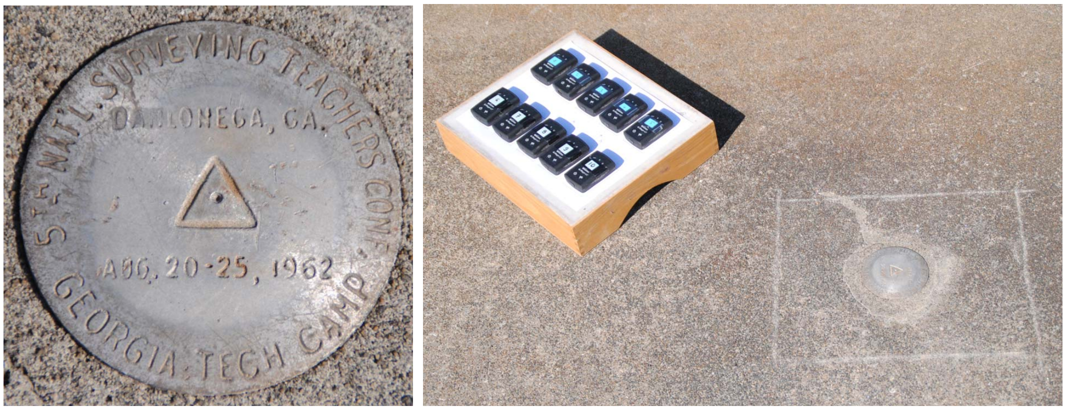
3.3.1 Stationary Tests

Unlike previous studies that have dealt with high-end, very accurate GPS devices, this work explores the potential of implementing low-cost GPS devices suitable for mass deployment. As previously explained, their error had to be tested. To measure the error the study uses two scales: absolute global scale and relative scale. The absolute scale is the measure of correctness of the global coordinates logged by the devices. The relative scale is the measure of the deviations exhibited by the devices when exposed to the same environmental conditions. Since many of the same GPS data loggers were deployed on the same construction site at the same time, knowing their relative accuracy can give a good sense of the level of accuracy to be expected when studying the interrelationship of spatio-temporal interactions of construction resources.

The measurement of the error of the devices on the absolute scale was done by comparing the coordinate logged by the device to a known coordinate point. A known GPS benchmark point DG2790 with coordinate $N\,33\,^{\circ}46.594$ $W\,084\,^{\circ}23.898$ in the North American Datum (NAD) 83 coordinate system was selected (see Figure 11a). This point was located on the roof of the Jesse W. Mason Building on the campus of the Georgia Institute of Technology in Atlanta, Georgia, USA. As shown in Figure 11b, ten GPS data loggers were placed in two rows (five units in each row) on a wooden board. The distances from the center of the board to the center of each of the units were measured manually with a tape to later relate the GPS loggers position back to the benchmark point. The wooden board was oriented to the north for proper correction of these offsets. A guiding rectangle was marked around the benchmark point so that the center of the board coincided with the center of the benchmark point (Figure 11b). Readings of all loggers were taken every ten minutes.

Since the GPS devices had motion detectors, leaving the devices at a point over a period of time produced identical data points. Hence, the devices were placed on the guiding rectangle around the benchmark point. The "push log point" function of the devices was used to create a flag point on each device with a unique ID. Thereafter, the units were carried more than 10 m away from the benchmark to ensure that the next reading on the known GPS reference point was independent of the previous one. This process was repeated a total of 36 times. The experiment was conducted on a day with no precipitation and minimal cloud cover.

Table 3 shows the error analysis of the GPS data logging devices compared to the known position of a GPS benchmark point. The distances above the diagonal represent the mean of the distances between the GPS logging devices, while the portions below the diagonal are the standard deviations of the distances between corresponding devices. The mean and standard deviation of the distance between the GPS devices and the benchmark point are listed on the right hand side of the table.



(a) Benchmark point DG 2790 (b) Apparatus setup for GPS Error Test

Figure 11: Evaluation of absolute error of the GPS data loggers.

Table 3: Error analysis of GPS data logging units placed on benchmark point DG 2790 (N=36).

GPS data logger ID		1	2	3	4	5	6	7	8	9	10	Benchmark	
		Mean distance between data loggers [m]										Distance [m]	Std. Dev.[m]
1	Std. dev. Of distance between data loggers [m]		0.64	0.55	0.52	0.75	1.06	0.85	0.84	0.70	0.59	1.06	0.43
2		0.44		0.36	0.55	0.68	0.83	0.64	0.64	0.36	0.67	1.02	0.42
3		0.47	0.37		0.58	0.63	0.96	0.71	0.66	0.43	0.60	1.00	0.41
4		0.45	0.41	0.41		0.73	1.12	0.90	0.87	0.73	0.54	0.96	0.40
5		0.58	0.50	0.53	0.57		0.87	0.77	0.78	0.72	0.82	1.08	0.37
6		0.66	0.59	0.58	0.69	0.50		0.55	0.68	0.89	1.15	1.36	0.41
7		0.44	0.42	0.48	0.40	0.51	0.45		0.50	0.68	0.93	1.24	0.44
8		0.45	0.52	0.58	0.55	0.48	0.54	0.32		0.68	0.94	1.31	0.33
9		0.51	0.49	0.42	0.52	0.47	0.71	0.57	0.67		0.69	1.04	0.51
10		0.48	0.39	0.44	0.44	0.54	0.66	0.50	0.50	0.47		0.87	0.39
												Mean distance[m] = 1.10	

$$a_{ij} = \begin{cases} Mean\ of\ the\ distance\ between\ GPS\ devices\ i\ and\ j & \text{if } i < j \\ Standard\ deviation\ of\ the\ distance\ between\ GPS\ devices\ i\ and\ j & \text{if } i > j \end{cases}$$

where, a_{ij} is any element of the table $(row = i, column = j)$ (except the last two columns which represent the distance and standard deviation from the benchmark point).

The maximum distance between the actual coordinate and the coordinate read by the data loggers was 1.36 m, which can be seen in GPS data logger # 6. The minimum distance of 0.87 m was found in unit # 10. The overall mean of the distances was 1.10 m. The standard deviation was high compared to the value of the mean, indicating a high deviation of individual values from the mean. The result indicates that for environmental conditions with an open sky , the error of the used GPS devices can be expected to be up to 1.1 m large, with a standard deviation of 0.41 m. The box plot in Figure 12 shows the distribution of the values in each dataset.

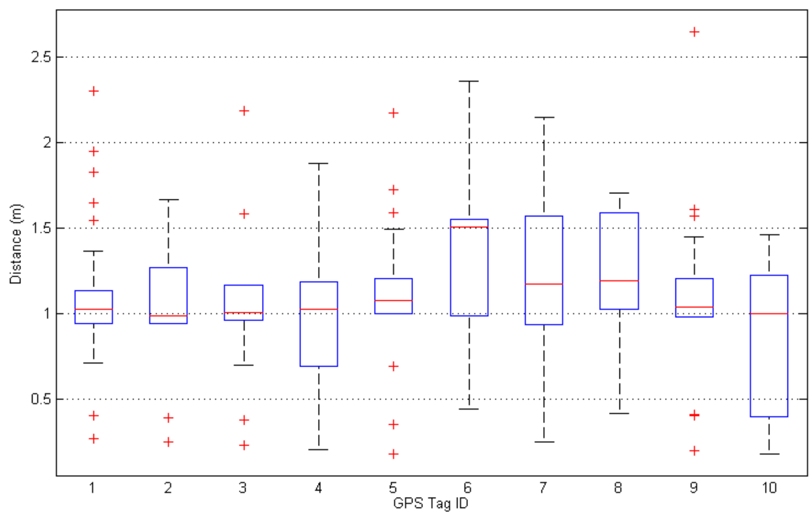


Figure 12: Box plot of the distance between the GPS data logging devices and benchmark point.

For the data collected on the construction site, the data loggers installed inside the construction equipment cabin and on the hardhats of workers could be obstructed by other construction resources such as overhead equipment cabins or materials. Overhead obstructions including roof positions or worker's head pose orientation continuously change as does the line-of-sight of the data logger to the sky. Hence, similar GPS data accuracy may not be expected on a typical construction site.

3.3.2 Non-stationary Tests

Stationary tests do not represent the actual deployment conditions of data loggers on site. Hence, the data loggers need to be tested while they are in motion. Furthermore, occlusions that block the view of the sky also affect the accuracy of the devices. Hence, a test was performed in an actual construction site to accommodate all the potential sources of error and to understand the nature of error at different areas inside the site.

Data were collected simultaneously using both Differential GPS (DGPS) and the low-cost GPS data loggers selected for data collection. A rover rod for DGPS was utilized to mount 10 GPS data loggers. These data loggers were attached to the rod at different elevations. Figure 13 shows the assembly. A real construction site described in 3.4.1 was chosen for data collection. Data were collected inside the site by walking in the trajectory so as to cover as much area as possible. Some areas inside the site were not accessible because of parked equipment and the presence of construction material.

The trajectory recorded by all the technologies was compared. Figure 14 shows the trajectory of DGPS and three GPS data loggers. A Robust Kalman Filter was applied to the data. A Robust Kalman Filter can remove outliers and also incorporate the kinematic characteristics of the equipment [40] [23]. The accuracy of the reading can be used to identify outliers and correct and smooth the path. Figure 15 compares the raw data and filtered data after application of the Robust Kalman Filter.

Figure 14 clearly shows that the data contains significant error. Data from DGPS was synchronized with that from the data loggers by associating the timestamps. Since the frequency of data collection was 1Hz, only one data point was logged in one second. The tagged entity (worker or equipment) might move a significant distance in one second. Hence, this synchronization might introduce an error equal to the magnitude of the velocity of the entity. This lag is systematic and will be carried over throughout the synchronized data. A careful study of the magnitude and direction of error was done to understand the nature of error that can be expected on the site. The error was projected into North (x) and East (y) directions orthogonally

Figure 13: Assembly with DGPS and low-cost GPS data loggers for ground truth measurement (DGPS rover on the top and Wintec GPS on the rod).

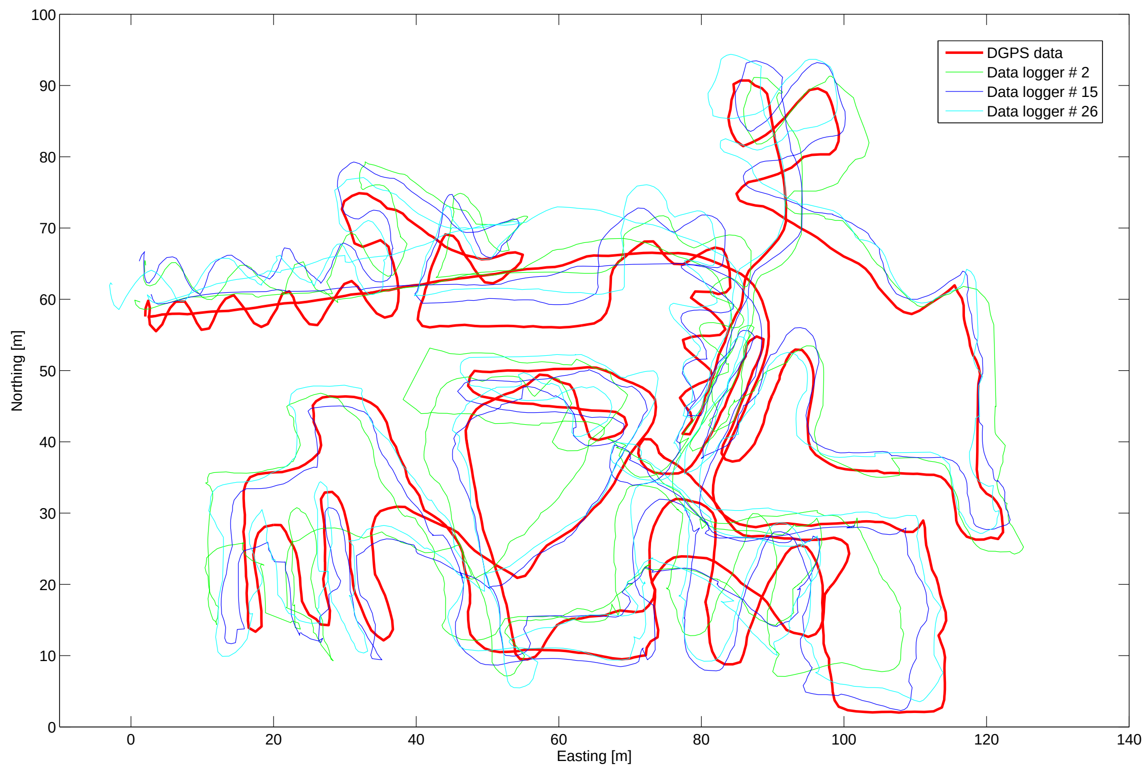


Figure 14: Trajectory recorded by the data loggers.

to analyze the nature of error in these two directions. An analysis of the absolute distance between the readings obtained from DGPS and the data loggers was also studied. Figure 16a and Figure 16b show that the magnitude of error in x and y directions varied with time.

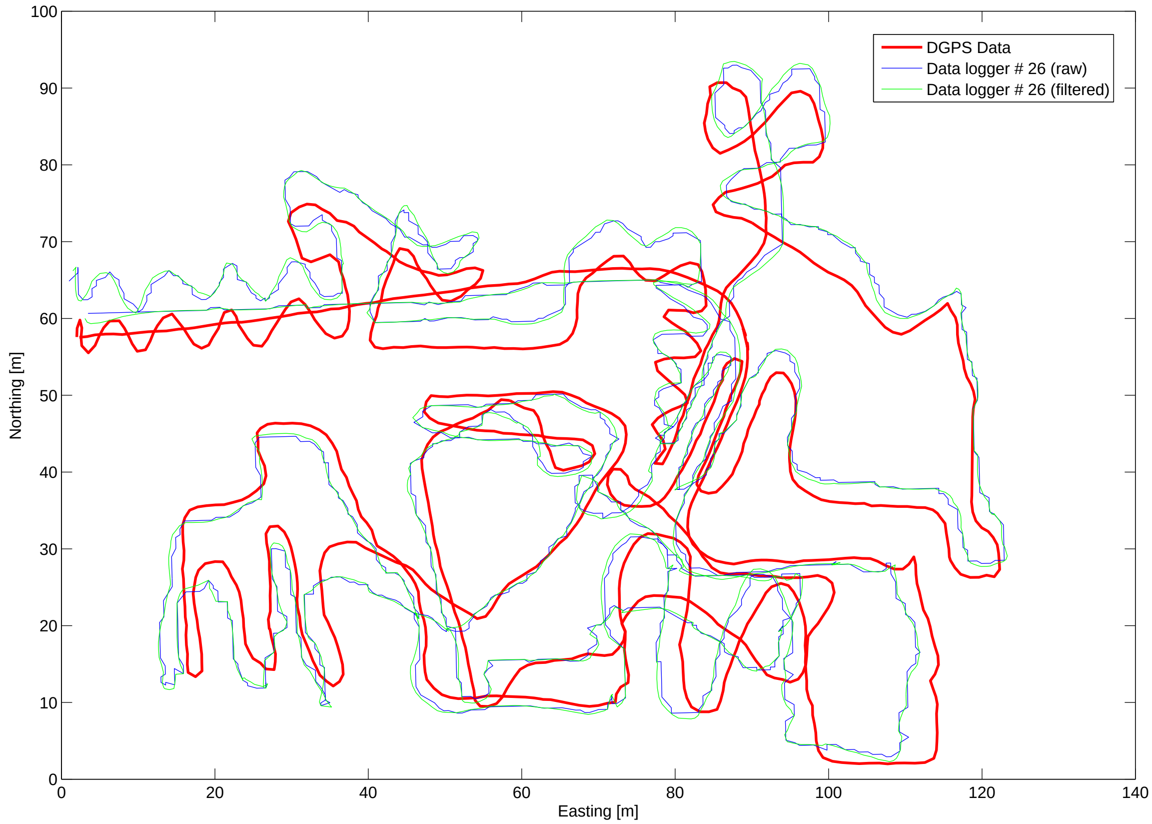
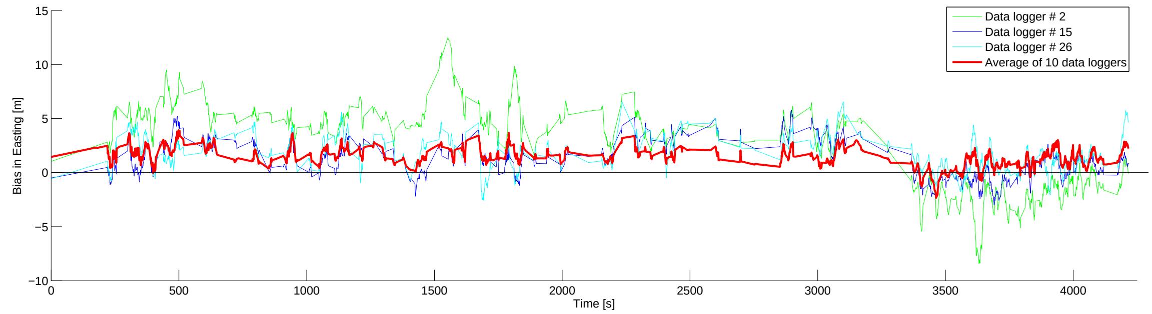
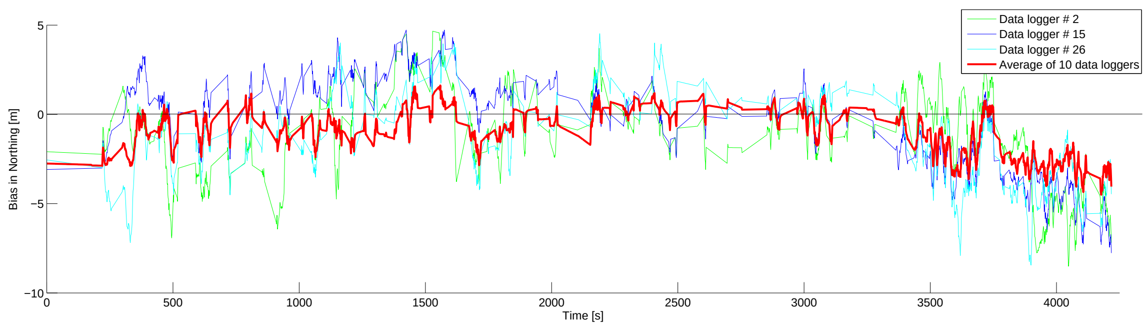


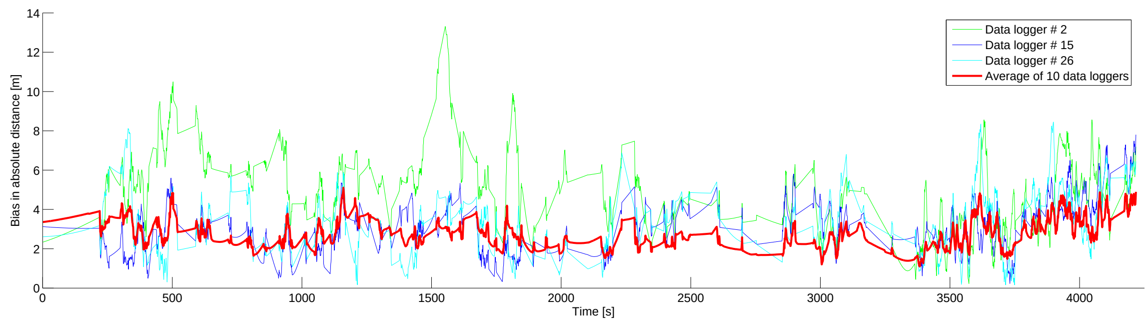
Figure 15: Result of data filtering.



(a) Error in Easting



(b) Error in Northing



(c) Error in distance

Figure 16: Analysis of error.

It was observed that the magnitude of error varied over time and was not consistently unidirectional. It was also observed that the magnitude of the error tends to correlate among different tags. Assessing the magnitude of the error in terms of location inside the site required plotting Figure 17, which shows the magnitude of distance error plotted in geographical reference. The data point representation was amplified by a cubical factor of the magnitude for visual clarity. The variation of

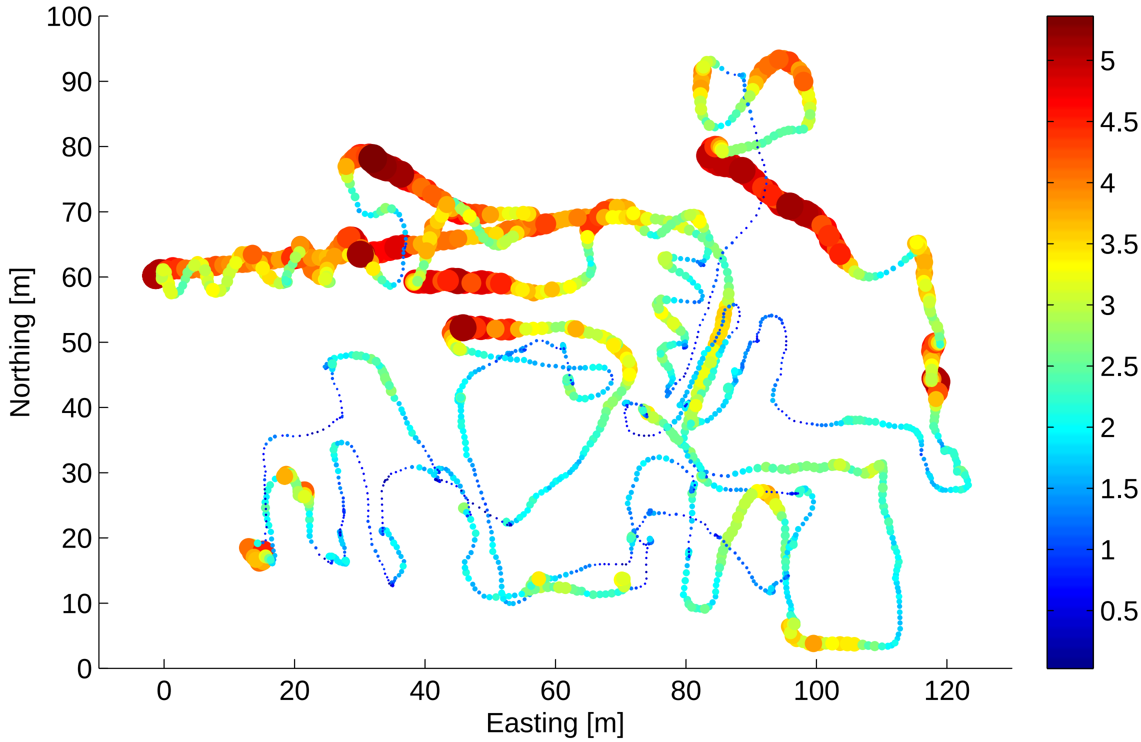
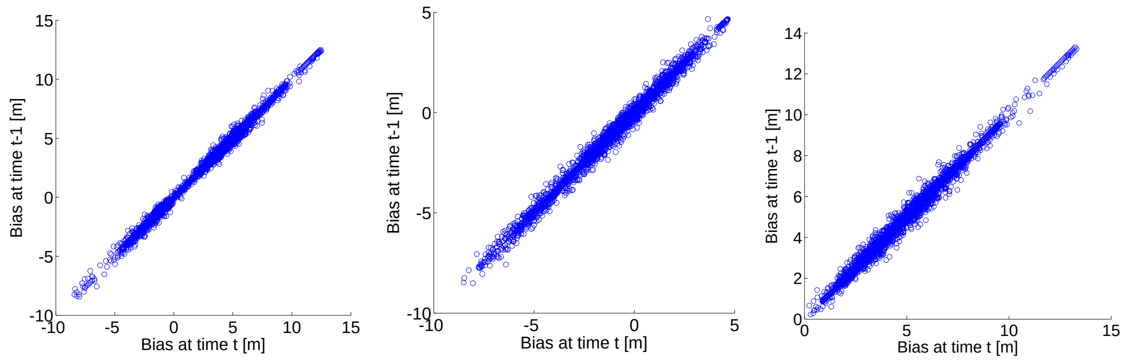


Figure 17: Error distribution (diameter of points amplified as a cubic function of magnitude of distance error, color based on magnitude of error).

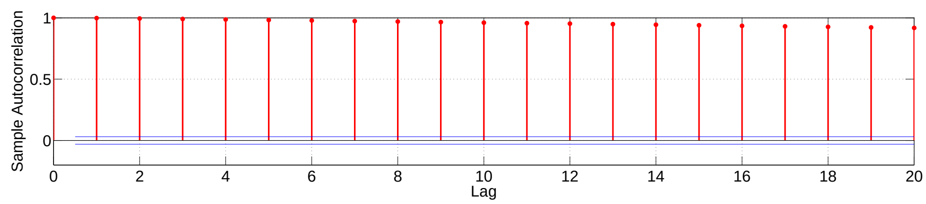
magnitude is also represented by variation in colors of the visualization of the points.

Figure 17 shows that the magnitudes of distance error were consistently high in some areas on site while other areas had relatively less error. This indicates that certain areas on site were exposed to more occlusions toward the visibility of sky compared to others. It was also noticed that the magnitude of error is not a random phenomenon and that it changes gradually along the trajectory inside the site (unless abruptly altered by a sudden occlusion, which was not observed in this particular site). An autocorrelation analysis of the error gives a clearer picture of randomness of error throughout the trajectory (Figure 18). Figures 19a, 19b and 19c show the autocorrelation plots.

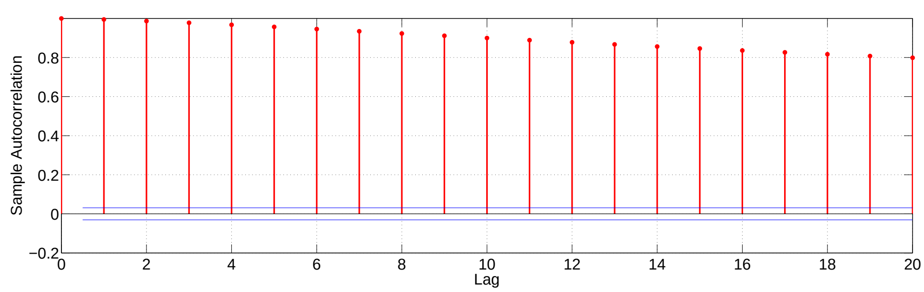


(a) Error in Easting (b) Error in Northing (c) Error in distance

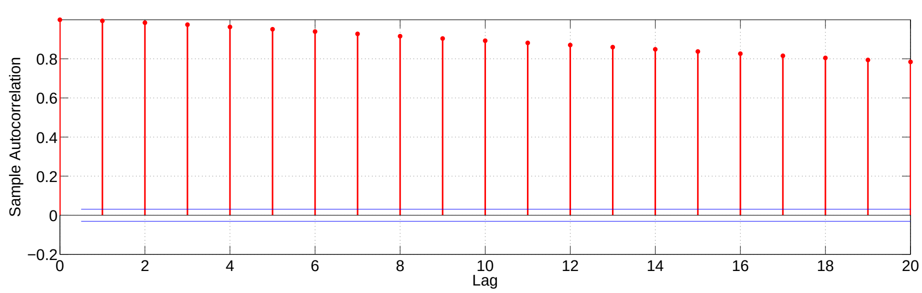
Figure 18: Autocorrelation plots.



(a) Autocorrelation in Easting



(b) Autocorrelation in Northing



(c) Autocorrelation in distance

Figure 19: Autocorrelation analysis.

It was observed that magnitude of error is not a random phenomenon and changed gradually inside the site as the trajectory progressed. This implies that there is a potential for localizing the error while correcting the location data.

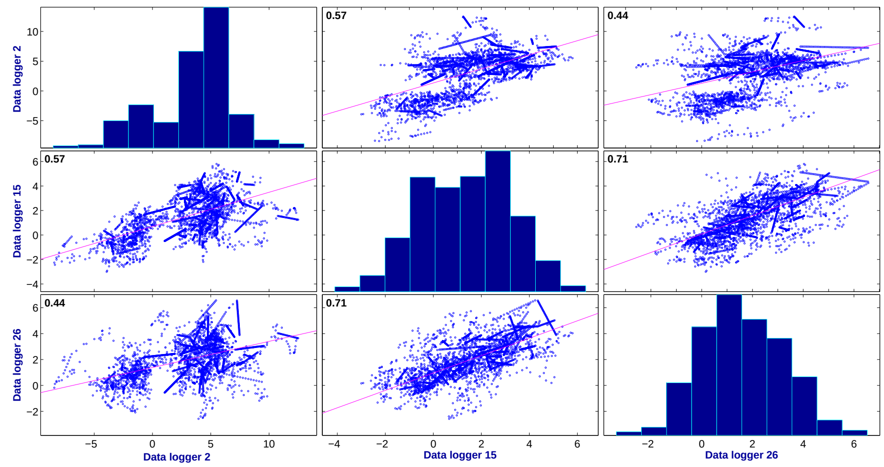
A study of the readings recorded by different data loggers was also done to examine the magnitude of error produced by different tags. Figures 20a, 20b and 20c show the correlation plot among three different data loggers deployed for data collection.

The figures are plotted in a matrix form. If each subfigure represents an element of the matrix a_{ij} $(row = i, column = j)$, then

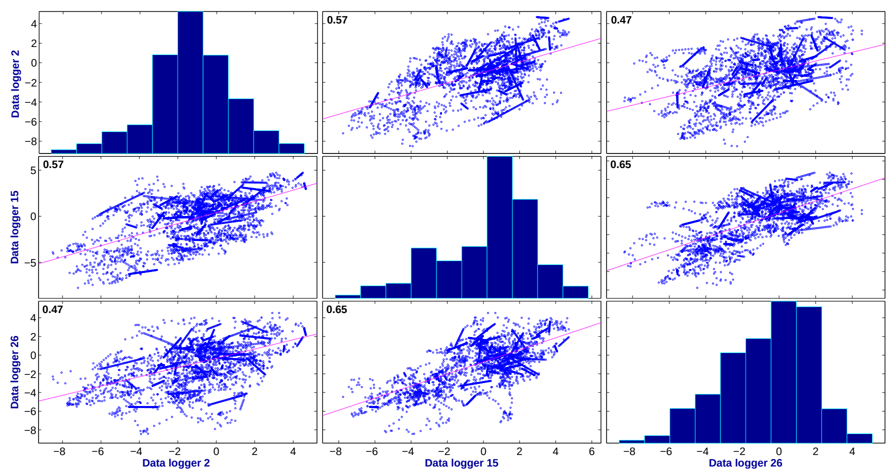
$$a_{ij} = \begin{cases} Histogram\ of\ error & \text{if } i = j \\ Correlation\ plot\ between\ data\ loggers\ i\ and\ j & \text{if } i > j \\ Correlation\ plot\ between\ data\ loggers\ j\ and\ i & \text{if } i < j \end{cases}$$

Although a positive correlation was observed in each case, the correlation was not strong, as shown in the figures. This indicates that the error in different data loggers does not follow the same function throughout the trajectory. A strong correlation would indicate that the magnitude of error in one data logger cannot be generalized to address error produced by other data loggers. The correlation plots also showed several linear components, indicating that the error in two data loggers are highly correlated at certain parts of the trajectory and that the correlations change in different areas of the site. The reason for this might be the motion pattern of the entity or the view of sky available to that particular data logger at that stretch of the trajectory.

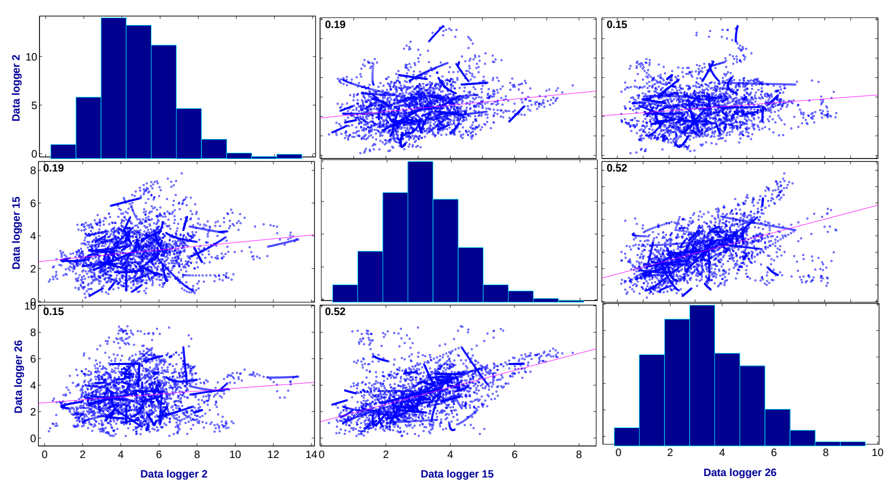
Figure 21 shows the distribution of error that was observed in each instance while covering the trajectory shown in Figure 14. Figure 21 shows the observations recorded by all 10 data loggers accounting for 42,170 points. Figure 21 shows that the mean observation was 1.56m towards the east and 0.83m towards the south of the actual point. Figure 21 also shows the 50 and 95 percentile circles. The observation was within a range of 2.76m 50% of the time and within 5.90m 95% of the time.



(a) Correlation plot for Easting



(b) Correlation plot for Northing



(c) Correlation plot for distance

Figure 20: Autocorrelation analysis.

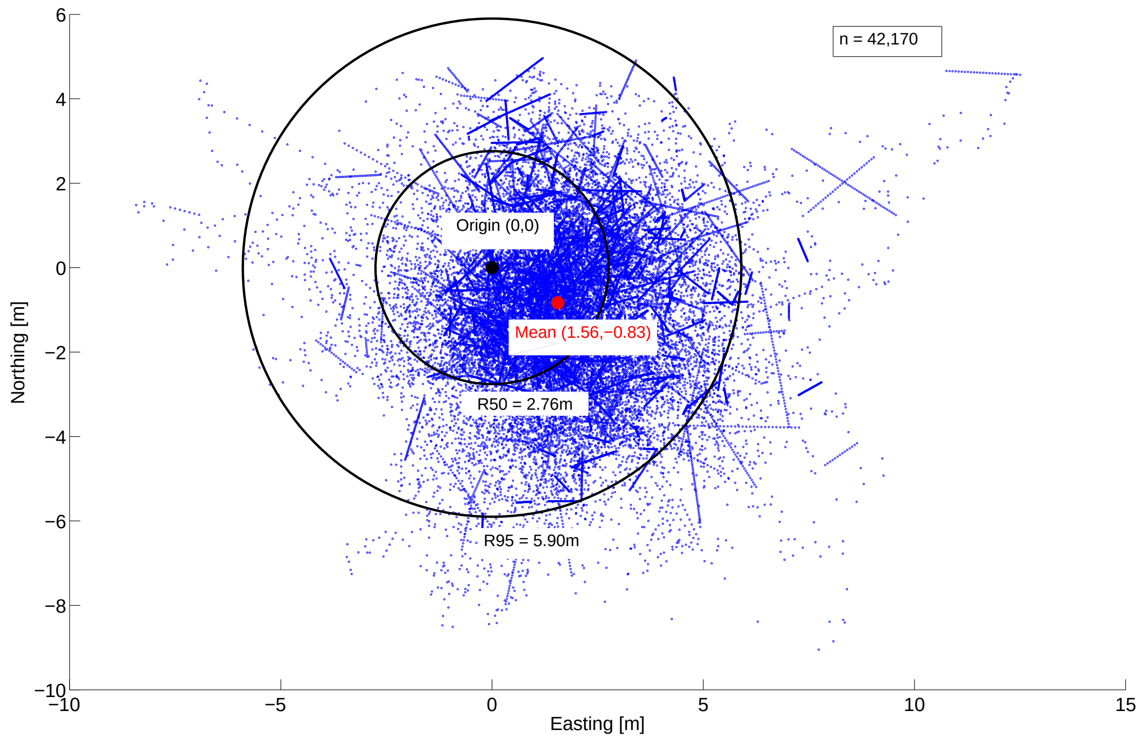


Figure 21: Error distribution.

Figure 22 shows the percentile distribution of the error observed. The 50 and 95 percentile points are marked in red. Figure 22 gives an idea of the confidence interval that can be expected in the observations. The curve steepens after 95% because of the outliers present in the observations.

After the nature of error was analyzed, it was concluded that the error in reading cannot be locally distributed because it is not dependent upon the location inside the site. The presence of strong autocorrelation suggests that the error is not random. However, it was observed in Figure 20 that the correlation observed among consecutive data points is not consistent throughout the trajectory, and temporary correlations were observed in small spans of the trajectory. The accuracy requirement for different components of this research was reviewed, and the following decisions were made.

i Automated Operation Analysis

Cycle times of equipment and zone and speed analysis of their trajectory do not

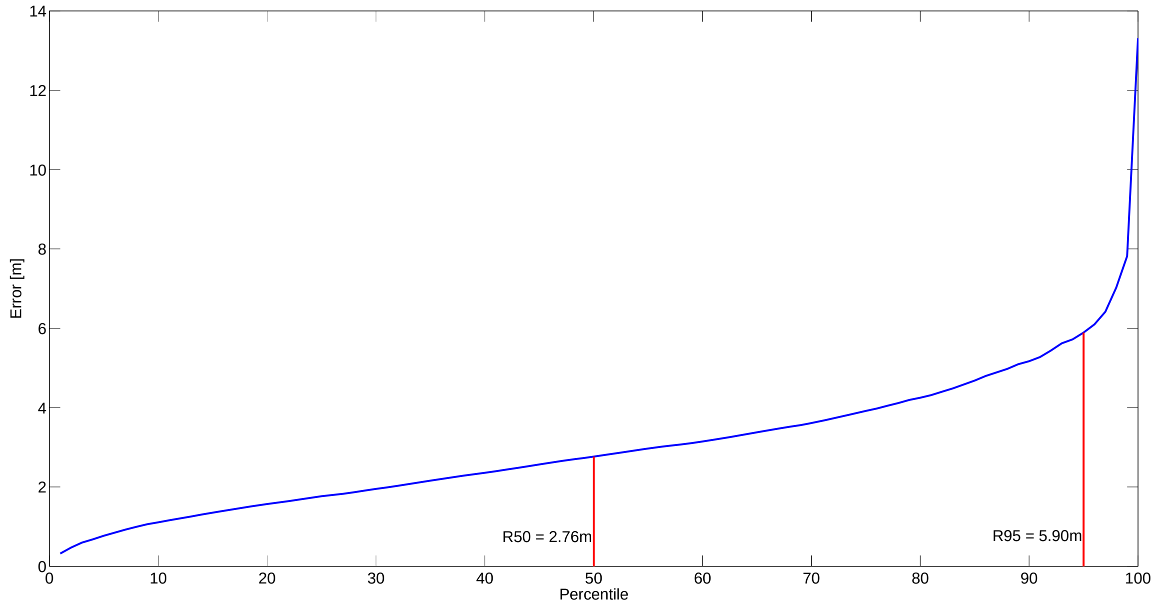


Figure 22: Percentile distribution of error.

necessarily require high precision systems because the boundaries of the zones are generally imaginary and depend upon many factors. The purpose of automating operation analysis is to eliminate human involvement in the observation process. A few meters of deviation in equipment location hardly affects the outcome significantly. Hence, the tested low-cost GPS was considered acceptable for this purpose .

ii Cell-based Simulation

Simulation usually involves modeling stochastic processes into a mathematical model. In the case of an earthmoving operation, timestamps of the activities are more important than the precise location of the occurrence (Section 5.4). Since the site geometry is acquired from a different source, to a significant extent, the simulated trajectory is not influenced by the trajectory of the actual equipment. The inaccuracy might alter loading time because the location of the excavator also suffers from the same error. This will consistently change the loading time for trucks inside the site, keeping the model as a whole unaffected. The devices were also found acceptable for this purpose.

iii Construction Site Hazard Mapping

Hazard mapping deals with workers interacting with equipment. In this case, a higher accuracy is desired. Further tests are needed to deploy the devices for this purpose. Experiments done in a controlled setup, one in which the results are known beforehand, can be a method of evaluating the technology's reliability.

3.4 Data Collection

An example of the extent of data collected from the site is given here.

3.4.1 Engineered Biosystems Building

3.4.1.1 Site Description

The Engineered Biosystems Building (EBB) being constructed on the Georgia Institute of Technology campus is located at the intersection of 10th Street and State Street. The entire site is approximately 120m x 100m. The total volume of excavation was 40,000 cubic yards (CYs) of earth. The excavation began on November 28, 2012 and lasted till February 18, 2013. The excavation process was interrupted several times because of weather and for other reasons. The site contains the excavation pit, driveways, trailers for the site office, a material storage area, and restrooms etc.

3.4.1.2 Data Available

The details about these different types of data were been given in Chapter 3.1. The following is a quick preview of the data available for analysis.

- Real-time Location Data : Real-time location data from the resources forms the basis of the analysis for this research. Data collection done at a 1Hz frequency is used to analyze the trajectory of the resources at each instance.

Figure 23: Overview of the site.

Figure 24: GPS data logger on an excavator.

Figure 25: GPS data logger on a truck.

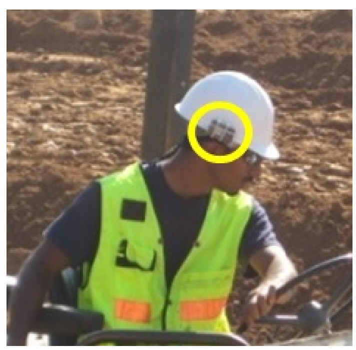


Figure 26: GPS data logger on a worker's hard hat.

- Building Information Model: A BIM is used as a reference for site geometry. Structural elements on the site were compared with the schedule in the BIM and laser scanned for accurate geometrical dimensions and locations.

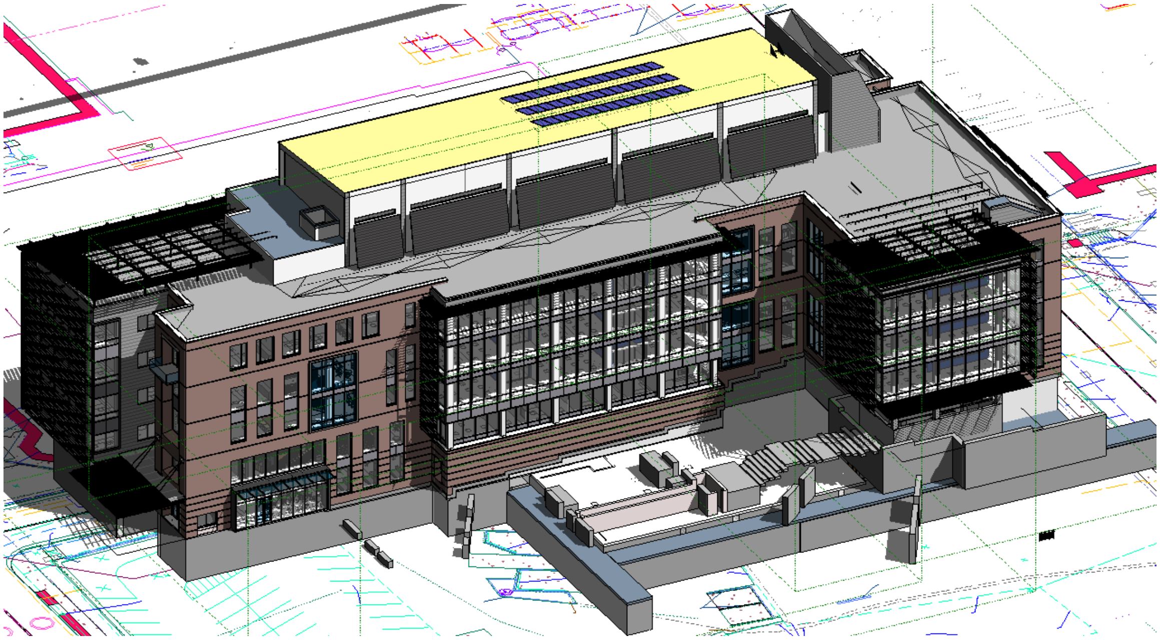


Figure 27: BIM of the building.

- Laser Scan: As mentioned above, a laser scanner can collect the exact as-is condition of the site. The data was used to identify objects on site that can act as occlusions and alter the blind spot maps of the equipment.

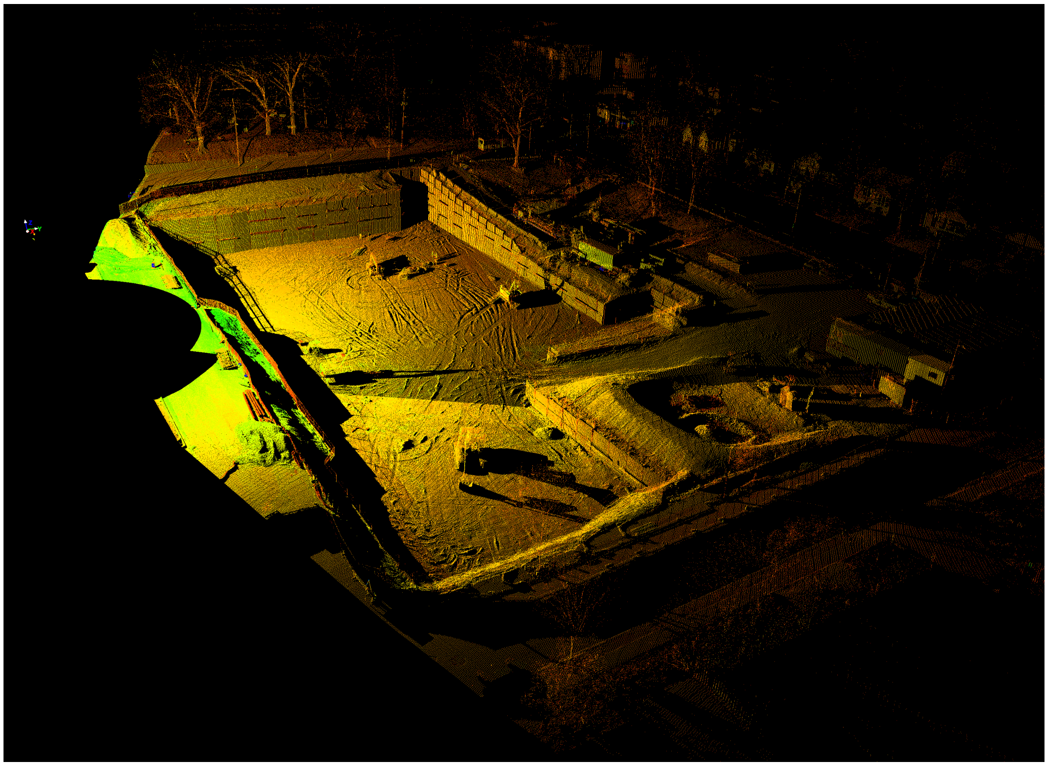


Figure 28: Laser scan data from the site.

- Pictures and Video: Pictures and video taken at the site can give information about the location of the workers and equipment at the time they were taken. They can also record the site conditions under which the resources were operating. The data from the video and pictures are used in this research for verifying the results obtained from the automated method compared to the actual information from the site.

(a) OxBlue Camera

(b) Manually taken pictures

Figure 29: Pictures and video data from the site.

- Aerial Imagery: Aerial imagery is primarily used for plotting the trajectory and results from analysis for easier understanding. It can also be used to map the actual site layout and compare it with the site layout plan on paper.

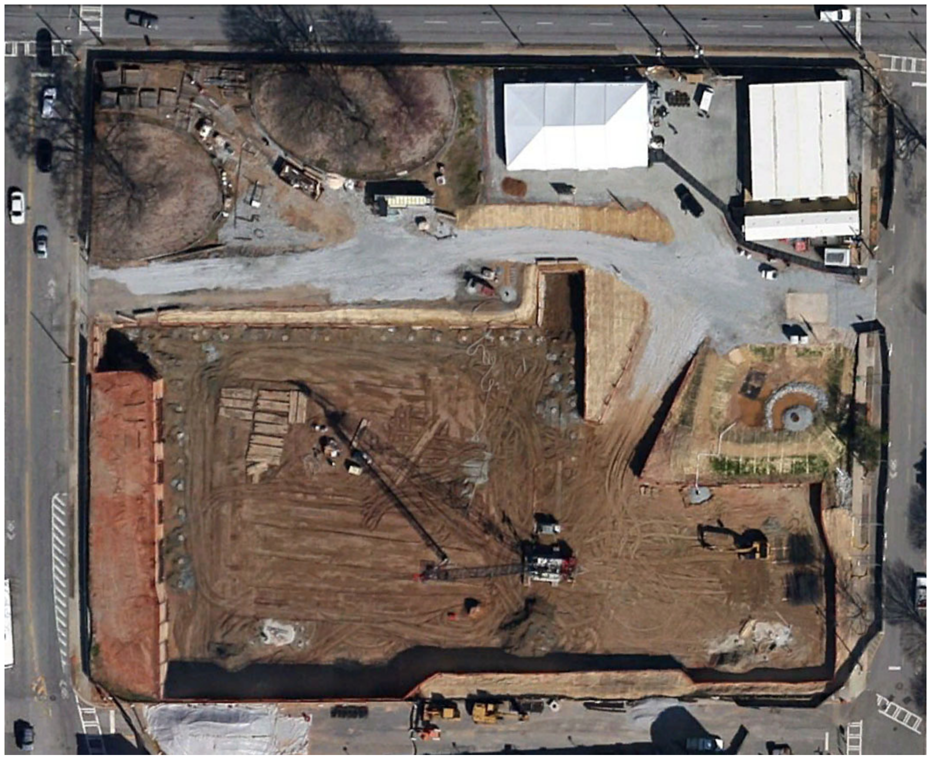
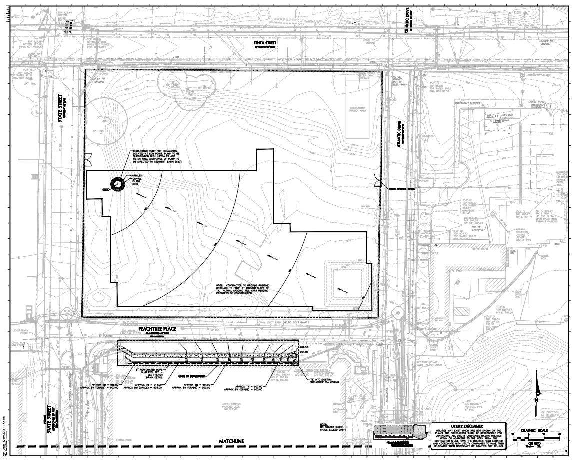


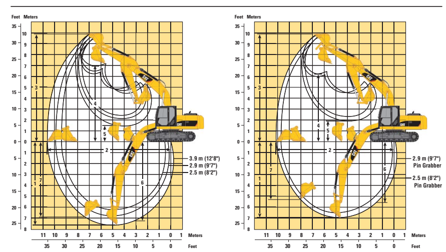
Figure 30: Satellite imagery of the site.

- Site Layout: Map Site layout map is used to derive the different zones at the site and automate the hazard identification process based on access of the resources to those zones.

- Resource Information: Information about resources like the dimension, capacity of load, and production rate are used to model their kinematic behavior. It is utilized in analyzing blind spots of the equipment, proximity requirements, and hazard levels associated with performing specific tasks.



(a) Site layout map



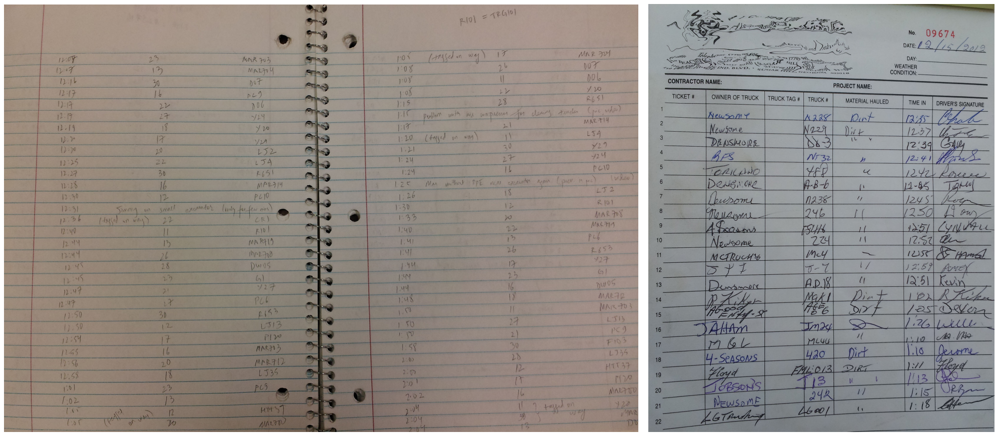
Boom Options	Reach 5.68 m (18'7")	Reach 5.68 m (18'7")	Reach 5.68 m (18'7")	Reach 5.68 m (18'7")	Reach 5.68 m (18'7")
Stick Options	R3.9B1 m (12'8")	R2.9B1 m (9'7")	R2.5B1 m (8'2")	R2.9B1 m (9'7")	R2.5B1 m (8'2")
Bucket	1.0 m³ (1.31 yd³)	1.0 m³ (1.31 yd³)	1.0 m³ (1.31 yd³)	Pin Grabber Quick Coupler with 1.0 m³ (1.31 yd³)	Pin Grabber Quick Coupler with 1.0 m³ (1.31 yd³)
1 Maximum Digging Depth	7660 mm (25'2")	6720 mm (22'1")	6300 mm (20'8")	6980 mm (22'11")	6560 mm (21'6")
2 Maximum Reach at Ground Level	10 760 mm (35'4")	9860 mm (32'4")	9460 mm (31'0")	10 120 mm (33'2")	9730 mm (31'11")
3 Maximum Cutting Height	9940 mm (32'7")	9490 mm (31'2")	9290 mm (30'6")	9720 mm (31'11")	9520 mm (31'0")
4 Maximum Loading Height	6940 mm (22'9")	6490 mm (21'4")	6290 mm (20'8")	6230 mm (20'5")	6030 mm (19'9")
5 Minimum Loading Height	1230 mm (4'0")	2170 mm (7'1")	2590 mm (8'6")	1910 mm (6'3")	2330 mm (7'8")
6 Maximum Depth Cut for 2440 m (8') Level Bottom	7270 mm (23'10")	6370 mm (20'11")	5950 mm (19'6")	5680 mm (18'8")	5290 mm (17'4")
7 Maximum Vertical Wall Digging Depth	6970 mm (22'10")	6060 mm (19'11")	5650 mm (18'6")	5380 mm (17'8")	4990 mm (16'4")

(b) Resource information

Figure 31: Site and resource information.

- Site Notes: Site notes are used to gather valuable information about crucial events at the site. For specific data types, manual observations can gather more information than the use of specific sensors. Site notes are also used to verify the results from automated methods compared to actual data from the site.

- Driver's Sign-in sheets: In the earthmoving operation being tracked, the drivers had to sign in to keep a record of the number of trucks that hauled on that day. This sign-in sheet was used to verify the number of loads made as calculated from the automated method.



(a) Site notes (b) Driver's sign-in sheet

Figure 32: Manual observations.

3.5 Data Management

A processing platform was developed using Visual C# 2010. The purpose of the platform was to visualize the data in an interactive manner. Further, a MATLAB API was created for complex matrix manipulations. Raw data, which was imported into the platform using a user interface, was filtered and stored in a Microsoft Access (.mdb) database.

Figure 33 shows the basic user interface that was developed. An image and a separate color can be assigned to each data logger, and the trajectories of the data logger(s) can be plotted in specified color(s). Animated replays of the data logger recordings can be visualized by pressing a time bar at the bottom of the interface. A background image, for example the site layout map, can be loaded by specifying the top left and bottom right coordinates. The interface allows synchronizing the site layout map coordinates with the data from the GPS devices. This enables accurate representation of the spatio-temporal movements of the resources on the construction site. GPS and time-referenced photos, which typically are taken on a project to document site or work progress, can also be uploaded in a user interface (see the left side of the interface).

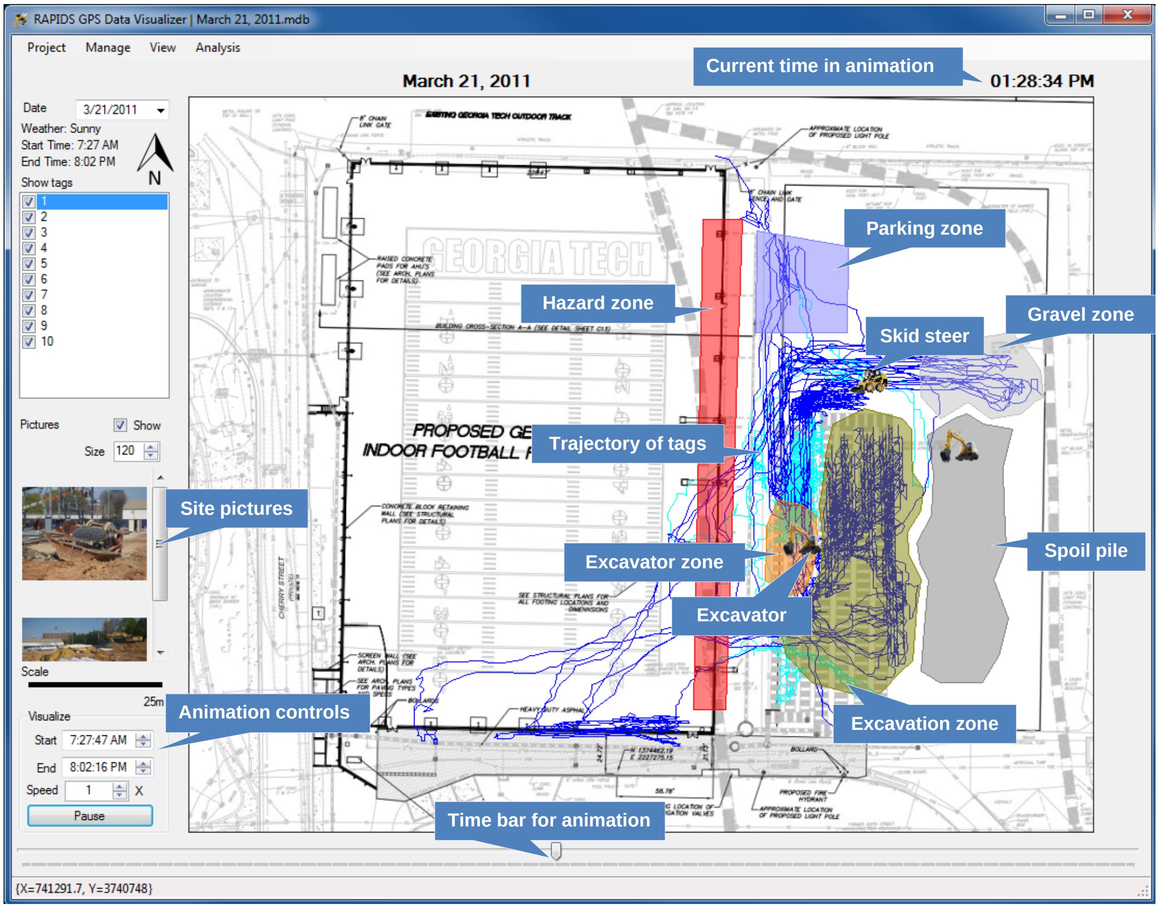
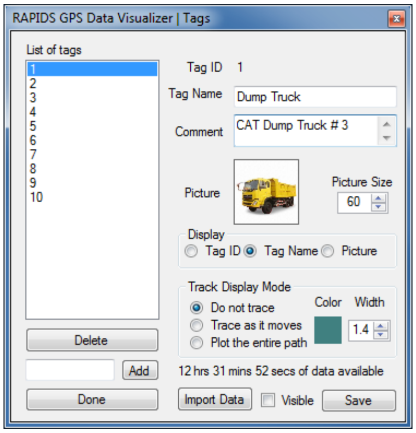


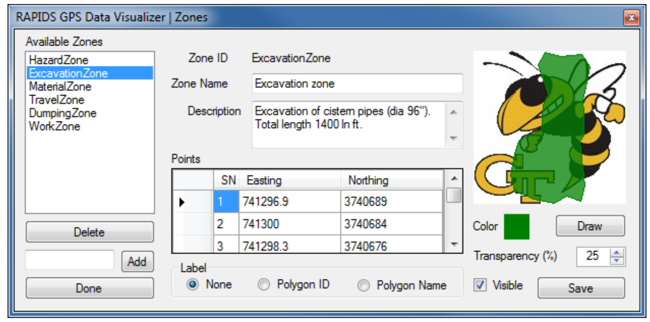
Figure 33: Developed user interface to display GPS data and other site and project management relevant information.

Figure 34a shows the user interface for adding a new resource/data logger to the system. Figure 34b shows the user interface to manage work zones. Zones can be defined and drawn directly on the plot plan shown in Figure 33. The coordinates of the points forming the zone can also be edited from the user interface for more accurate entries.

Once the site trajectory data of the resources using the GPS data loggers has been collected and the site and resource information is uploaded, the user interface can perfrom the following data processing: determination of any cyclic behavior of the resources, spatio-temporal interactions among the resources on site, zone and speed analysis, assessment of the behavior of the resources and their motion, proximity



(a) Managing data loggers



(b) Managing work zones

Figure 34: User interface for managing data loggers and work zones

analysis of two or more resources to identify the potential collision hazards on a construction site.

3.6 Summary

This chapter discussed the types of data that can be collected from a construction site and presented their current use in the construction industry.. The best fit for the purpose of the current research is low cost GPS technology. A detailed error analysis was done for GPS technology, and the conditions in which this data can be use was discussed. A test was done in stationary conditions to examine the error in ideal conditions. Another test was done in a non-stationary condition to understand the level of error in actual site conditions. It was concluded that the error could not be localized with additional information such as satellite information. The chapter then gave an example of how construction jobsites are becoming more and more data driven and concluded by introducing a platform developed for managing this enormous source of data. Following chapters will discuss how this platform can be used for analyzing safety conditions on site.

CHAPTER IV

AUTOMATED CONSTRUCTION OPERATION ANALYSIS

This chapter outlines the platform developed for automatic operation analysis. The major components of this chapter are zone and speed analysis, proximity event analysis and cyclic activities analysis.

4.1 Introduction

Outdoor construction sites are dynamic environments where construction resources (workers, equipment, and materials) continuously interact with each other. Recording accurate and reliable data from these interactions is critical for analyzing any construction site operation. Productivity analysis and activity sampling methods have been proposed in the literature and provide guidelines for observing, recording, and analyzing work tasks on construction jobsites [37]. These analyses are often conducted in a controlled workspace on a project and on only a few resources. Sample data are provided only for a short timeframe and may not allow a comprehensive study of all the resources on a project. Most analysis methods also use manual sampling methods that can be influenced by the person who is observing the operations and recording the data. Even though these existing work sampling techniques for operation analysis have proven to be useful and effective, the most common approach that has been taken has been manual data recording. Subsequently, the use of tablet computers and other technology has simplified the tasks in assessing the resources performance. However, the specially trained observers remain unable to collect detailed data continuously for larger jobsites and for when multiple pieces of resources might be operating simultaneously.

A common analogy is that safety performance is tied to productivity performance [114]. As the role of equipment in construction progress is large [35], leveraging technology for its productive and safe use supports general project objectives. However, existing equipment management methods are limited since few site staff can control progress and performance. Often activity performance control tasks are inadequate and less frequent [37].

In construction research, Oloufa et al. [95] were among the few researchers who explored the use of GPS in equipment operations analysis. Their investigation focused on a collision detection system for construction equipment. In hazardous environments where human presence is not encouraged, such a system can also wirelessly transfer GPS data to a central information management system. Potential applications of such a system could identify collision scenarios between equipment. In addition, Real-Time Kinematic (RTK) GPS has been introduced to control the vertical position measurement and the accuracy of the earths surface profiling [100]. GPS has also been used for equipment productivity tracking in waste management and on-site material management applications. GPS in combination with Geographic Information System (GIS) and Wide Area Network (WAN) serves as an important component in centralized monitoring systems [78]. Several researchers have tested the accuracy levels and performance characteristics of different GPS equipment with respect to the ability to successfully map GPS data to an underlying GIS network database [129]. Many commercial products utilize highly precise GPS technology for outdoor applications in agriculture [108], construction, and transportation [135] [21] [70].

Some recent academic studies have focused on the analysis of GPS data for construction operations analysis [62]. Others have utilized Personal Digital Assistant (PDA) technology for data collection in tunnel construction [131]. The most relevant approach to this work was done by Hildreth et al. [62], whose main contribution was that GPS data, once processed, could be directly fed into simulation models. The study further focused on identifying key values common in existing construction simulation models: load, haul, dump, and return times. The models included only a limited number of zones that were manually defined. The shape of each work zone was always rectangular and did not allow for more constrained site and work space restrictions.

4.2 Methodology

The outline of the process for construction site equipment operation analysis using GPS datails shown in the flowchart in Figure 35. The process includes three main components: the deployment of GPS technology, the data analysis platform, and the utilization of site geographic information. Section 4.3 describes the parts and capabilities of the developed automated operation analysis platform.

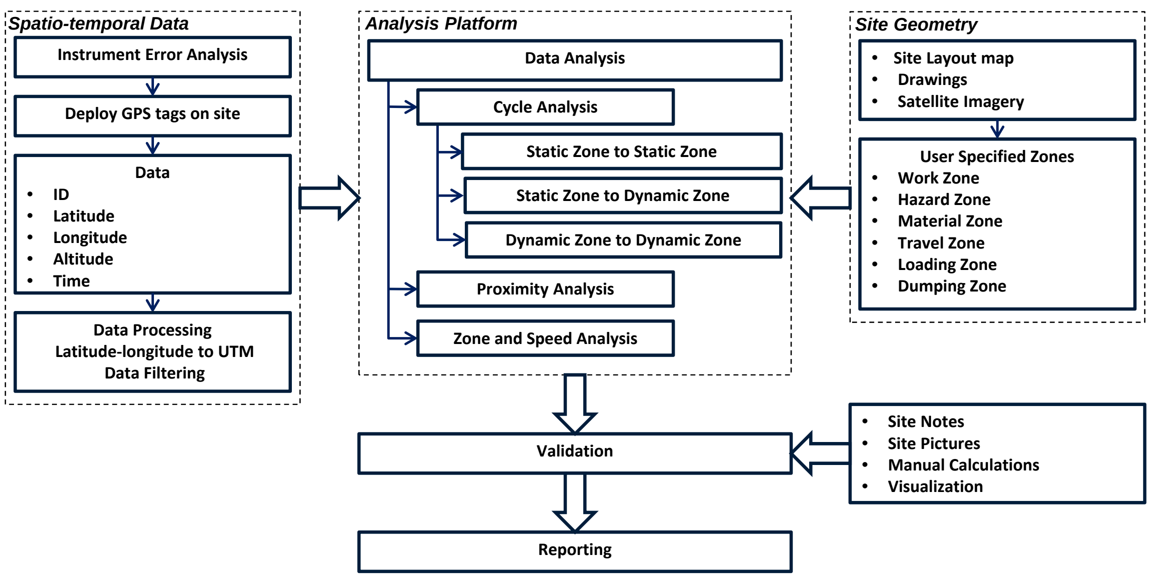


Figure 35: Process of embedding spatio-temporal data to equipment operation analysis.

4.3 Automated Operation Analysis

Algorithms for three major operations analyses were developed for this research,analysis of cyclic activities, zone and speed analysis, and proximity of incidents analysis. Each of these analyses is described with relevant real site examples below.

4.3.1 Analysis of Cyclic Activities

Cyclic activities are common in construction operations. A typical cyclic operation consists of a number of different repetitive activities. One example of a cyclic operation is earthmoving. which is composed of four major activities: loading, hauling, unloading, and returning. Each of these activities has time associated with it, which is of prime concern in planning those operations. In this case, the times would be load time, haul time, unload time, and return time. Load time is the time spent by the equipment loading material. Haul time is the travel time from the start zone (the loading zone) to the end zone (the unloading zone). Unload time is the time taken by the equipment to dump the material, and return time is the time it takes the equipment to travel from the dump zone back to the loading zone. Such cyclic activities can be automatically identified and analyzed using continuous spatio-temporal data. The amount of material hauled can also be estimated if the capacity of the equipment is considered. Such data can then be used for equipment productivity analysis. This research addresses only the identification and analysis of such equipment cycles. This analysis is crucial because the input analyses for simulation models are based on the result of this analysis.

The platform developed for the analysis of cyclic activities is shown in Figure 33. The analysis process relies on the following

- *A piece of equipment with attached GPS data logger:* It completes a cycle from start (e.g., load) to end (e.g., dump) zone and back. The trajectory of each GPS data logger is then analyzed.

- *Start zone:* This can be a static zone (one that does not change its position during the time of data collection) or a dynamic zone (a position that is time dependent). The time spent by the equipment in this zone will be considered "loading time". It includes loading time as well as preparation time. Since the static zones are manually drawn by the user and the dynamic zones are based on user defined rules, the loading time may slightly differ from the reality.

- *End zone:* Like the start zone, the end zone can also be a static or a dynamic zone. The developed algorithm requires that the start and end zones do not overlap. Similar to the start zone, the time spent in the unloading zone will be considered the time unloading material or finishing a task.

- *Time period of analysis:* This is a time filter. It includes the start and end time for detecting and analyzing cycles. If not specified otherwise by the user, the analysis will run for the entire dataset available from each data logger.

- *Range for dynamic zones:* Dynamic zones are created as circular regions around a GPS data logger. They are useful if start or end zones vary over time. The size of the radius of the circle can be specified by a user.

- *Maximum allowable travel time:* The maximum allowable travel time can be set by a user to avoid errors in the analysis. Setting such a threshold prevents potential cases where a piece of equipment leaves the site for a longer time than expected before returning or cases of equipment breakdown.

4.3.1.1 Static Zone to Static Zone

This analysis involves cyclic construction operations made from one static zone to another static zone, meaning that the start and end points of the cycle do not change as the operation continues. Examples of such fixed points are material storage area(s) and spoil/material pile(s), etc. A cycle is considered complete when a GPS-tagged resource that has left the start zone and entered the end zone returns to the start zone.

4.3.1.2 Static Zone to Dynamic Zone

This type of cycle is very common in linear repetitive projects as in the construction of highways, pipelines, and canals, etc. Cycles are made between a static fixed zone and another zone that changes its position over time. Let us suppose a case in which a dump truck is hauling earth from a spoil/material pile to an excavator for backfilling. After a certain time, the excavator will move to adjust its position to continue the backfilling. The start zone of the truck will always be the location of the spoil pile, but the end point will change as the excavator moves. A static zone can be represented by the zones drawn by a user on the site layout map. The position of the dynamic zone can be determined by a GPS data logger that is attached to the resource that changes its position. The radius specified by the user determines the size of the dynamic zone.

4.3.1.3 Dynamic Zone to Dynamic Zone

This analysis involves cycles made from one dynamic zone to another dynamic zone. The positions of both zones change over time, and trips made between these zones are analyzed each time based on the position of the zones at that instance of time. Section 4.4 will present an example in which a loader hauls earth from one excavator to another while the first excavator piles earth for another excavator, which is backfilling.

4.3.2 Zone and Speed Analysis

Knowing the distribution of time spent by the equipment in different work zones can give a good understanding of its utilization rate as well as the safety behavior of the resources. Equipment trajectories can be traced to see how often a piece of equipment enters a specified zone and how much time it spends in that zone. Another interesting piece of information construction managers like to know is the speed at which equipment travels in work zones. Equipment traveling at a higher-than-normal (or user-specified) speed inside a hazardous work environment/zone could be considered unsafe.

Internal Traffic Control Plans (ITCP) should be designed in such a way that construction equipment enter hazardous work zones only when absolutely needed and spend as little time as possible there. Detection and tracking of areas where equipment speed exceeds the permissible speed can also act as a leading indicator for construction site safety and help in detecting probable dangerous zones for pedestrian workers. Similarly, observing the movement of resources and their speed in different zones, including hazardous zones, can help determine requirements for equipment operator training or changes in traffic plans.

4.3.3 Proximity Incidents Analysis

Equipment working close to other equipment can cause hazards. Current methods of recording construction operations can record collisions only after they occur. Cases of near misses cannot be recorded without recording continuous data. Since the position of GPS-tagged equipment is known at high update rates, proximity analysis can be performed and instances where one piece of equipment operates too close to another one can be analyzed in terms of location and time. The integrating of such information into existing equipment operator education and training can improve site safety and productivity.

4.4 Results

4.4.1 Analysis of Cyclic Activities

4.4.1.1 Static Zone to Static Zone

The cycles between two static zones are shown in Figure 36. A skid steer loader delivered gravel material from a storage zone to a backfilling zone. A user defined the "gravel" zone by drawing a polygon on the site layout map using the developed

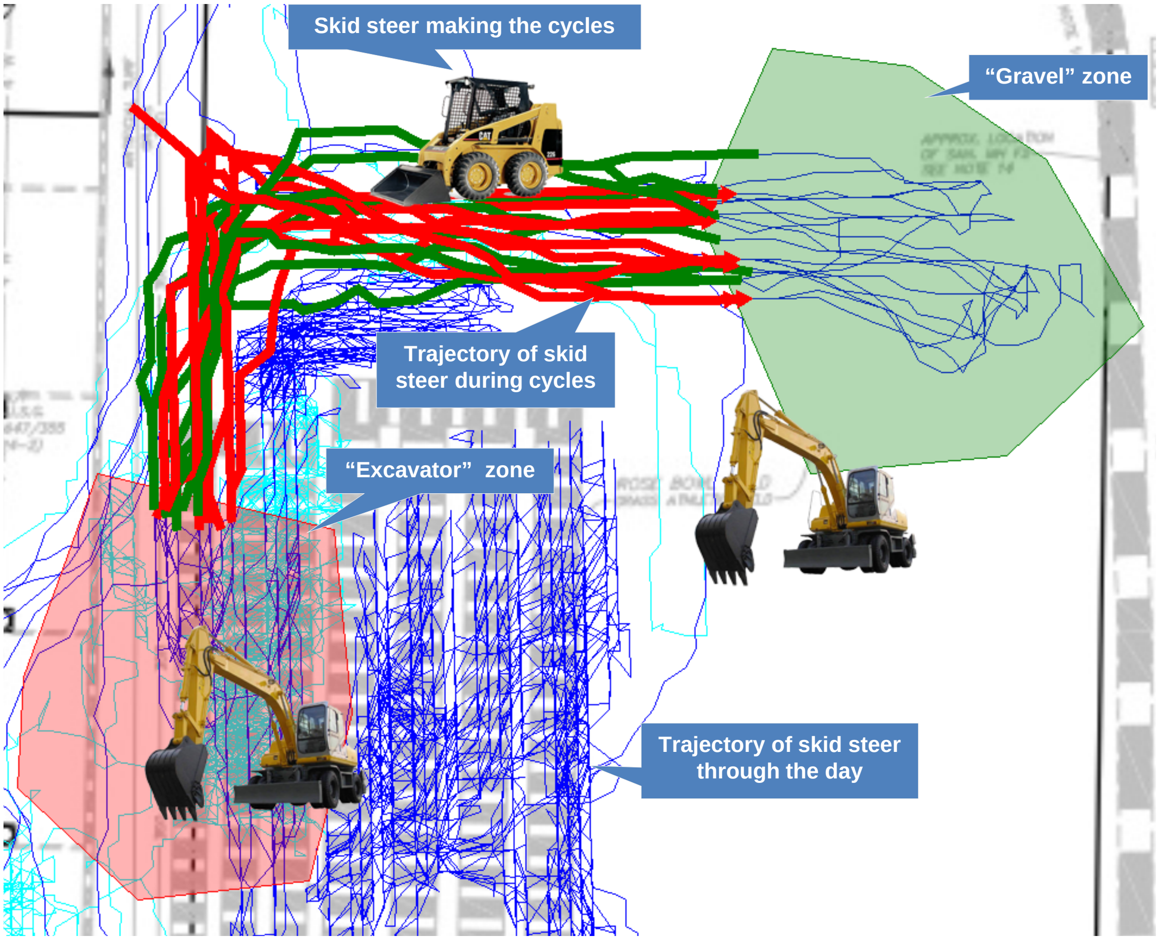


Figure 36: Cycle analysis : static to static zone.

platform. Since an excavator was located inside the backfilling area, a second fixed zone was assigned to the "excavator". The green and red paths in Figure 36 indicate movements of the skid steer loader from the "gravel" to the "excavator" zone, and vice versa.

The data in Table 4 shows the results of the cycles a skid steer loader made between these two zones. The "start time" and "end time" indicate the time when the skid steer loader left one zone to travel to the other. The "direction of travel" indicates the traveling direction between the zones. "Return time" represents the time it took the skid steer loader to travel from the excavator to the gravel after unloading its gravel at the excavator zone for backfilling. Similarly, "haul time" indicates the time it took for the skid steer loader to travel from the gravel to to the excavator zone (while carrying gravel). The "cycle time" is the time it took for the skid steer loader to complete one full cycle. "Unloading time" and "loading time" are the times the skid steer loader spent inside the excavator and gravel zones, respectively.

The time clock for a cycle starts/ends when the skid steer loader leaves the gravel zone or returns to the "gravel" zone. Since the last cycle may not include any further loading, the total number of completed cycles will be one less than the number of trips listed in Table 4.

Throughout the day of the testing, the skid steer loader made nine trips between the "gravel" and the "excavator" zones. The average haul and return times were 29 and 33 seconds, respectively. The return time was slightly higher than the haul time because the skid steer traveled in reverse from the excavator back to the gravel zone. Travel in reverse is, in many ways, more challenging and dangerous for an operator because of limited visibility. The average loading and unloading times were 29 and 23 seconds respectively. Generally, loading material takes more time than unloading it.

4.4.1.2 Static Zone to Dynamic Zone

Figure 37 shows a wheel loader that delivered gravel from the "gravel" zone to an excavator tagged with 37 data logger #3. While the loader continued to deliver gravel to the excavator, it should be noted that the excavator moved its position from "Position 1" to "Position 2" (see Figure 37) during the course of the data collection. This example demonstrates a simple case in which the excavator position changed only once. In reality, its position might be continuously changing, which may make accurate data analysis using fixed and manually defined zones impossible.

The results presented in Table 5 show that the wheel loader made 21 trips between the "gravel" and the "excavator" zones. A 15-m radius (user-defined) around the position of the excavator defined the unloading zone. Only cycles in which haul and

Table 4: Cycle analysis : static zone to static zone.

Travel [No.]	Start time [HH:MM:SS]	End time [HH:MM:SS]	Direction of travel [From→To]	Distance [m]	Haul time [MM:SS]	Return time [MM:SS]	Cycle time [MM:SS]	Unload time [MM:SS]	Load time [MM:SS]	Haul speed [km/h]	Return speed [km/h]
1	01:17:48 PM	01:18:14 PM	Gravel→Excavator	43.20	00:26		01:51		-	5.98	
	01:18:42 PM	01:19:11 PM	Gravel←Excavator	50.28		00:29		00:28			6.23
2	01:19:39 PM	01:20:05 PM	Gravel→Excavator	44.48	00:26		01:35		00:28	6.16	
	01:20:19 PM	01:20:45 PM	Gravel←Excavator	45.92		00:26		00:14			6.37
3	01:21:14 PM	01:21:41 PM	Gravel→Excavator	47.83	00:27		01:31		00:29	6.37	
	01:21:51 PM	01:22:19 PM	Gravel←Excavator	47.87		00:28		00:10			6.16
4	01:22:45 PM	01:23:19 PM	Gravel→Excavator	43.23	00:34		01:54		00:26	4.57	
	01:23:43 PM	01:24:14 PM	Gravel←Excavator	43.33		00:31		00:24			5.04
5	01:24:39 PM	01:25:06 PM	Gravel→Excavator	44.93	00:27		02:07		00:25	5.98	
	01:25:36 PM	01:26:08 PM	Gravel←Excavator	48.17		00:32		00:30			5.44
6	01:26:46 PM	01:27:13 PM	Gravel→Excavator	46.37	00:27		01:40		00:38	6.19	
	01:27:30 PM	01:28:02 PM	Gravel←Excavator	49.20		00:32		00:17			5.54
7	01:28:26 PM	01:28:54 PM	Gravel→Excavator	45.13	00:28		01:50		00:24	5.80	
	01:29:12 PM	01:29:41 PM	Gravel←Excavator	51.22		00:29		00:18			6.37
8	01:30:16 PM	01:30:50 PM	Gravel→Excavator	47.78	00:34		01:53		00:35	5.08	
	01:31:05 PM	01:31:39 PM	Gravel←Excavator	54.31		00:34		00:15			5.76
9	01:32:09 PM	01:32:37 PM	Gravel→Excavator	47.49	00:28		-		00:30	6.12	
	01:33:25 PM	01:34:21 PM	Gravel←Excavator	55.04		00:56		00:48			3.53
			Min		00:26	00:26	01:31	00:10	00:24	4.57	3.53
			Max		00:34	00:56	02:07	00:48	00:38	6.37	6.37
			Average		00:29	00:33	01:48	00:23	00:29	5.80	5.62

return times were less than 10 minutes were considered. All other trips were not considered as they most likely involved other work activities of the wheel loader. As explained before, the excavator changed from "Position 1" to "Position 2" at precisely 9:25 A.M. in the morning.

The average haul and return times were 58 and 38 seconds, respectively. Since no significant change in the haul or return time can be noticed for cycles to "Position 1" or "Position 2", the speed of the loader to "Position 2" must have increased to compensate for the time loss related to a larger distance. The variation in the haul and return time was high compared to the first case. The average cycle time was 3 minutes and 10 seconds. The average loading time was 1 minute and 13 seconds, while the average unloading time was 19 seconds. Loading time is generally the time it takes the equipment to load the material, but in this case, it started/ended at the moment the loader entered/left the "gravel" zone. It is likely that the loading/unloading time also includes some preparation time for loading.

4.4.1.3 Dynamic Zone to Dynamic Zone

A wheel loader hauling earth from one excavator to another is shown in Figure 38. The first excavator (tagged with GPS data logger # 4) piled earth that a second excavator (tagged with GPS data logger # 2) used for backfilling. Since the loader was not in operation most of the time during the observation day, its operator was tagged instead. Ideally, both are tagged to measure which operator drives which piece of equipment. A 15 m radius around each excavator was considered the loading and unloading zone. The trajectories of the loader shown in Figure 38 illustrate the time span for hauling earth material from 1:30 to 2:00 P.M.

Table 6 shows the results of the analysis. A total of five trips were made during the observation period. Average hauling and return times were found to be 27 and 26 seconds respectively. The haul and return times were somewhat consistent as

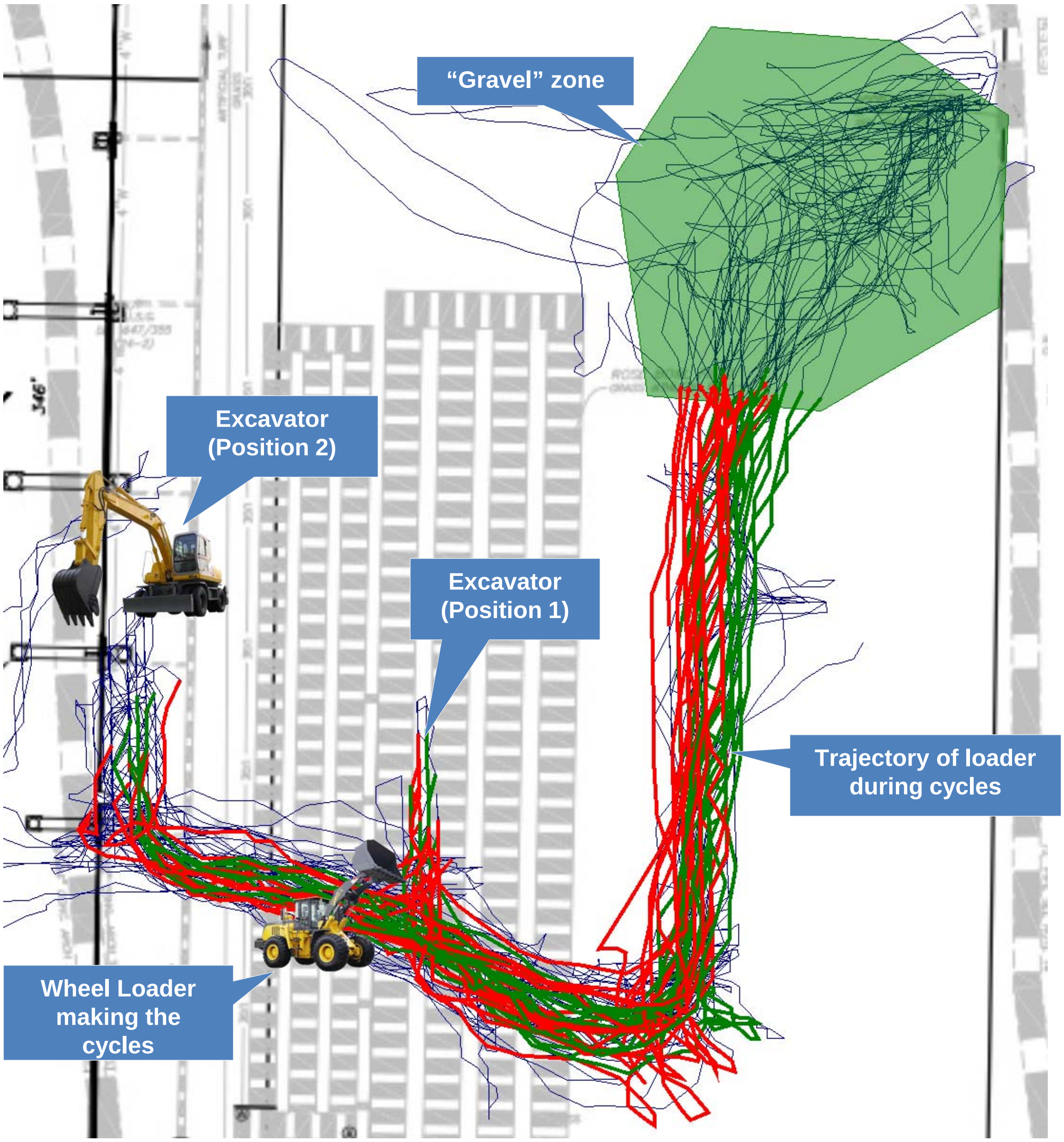


Figure 37: Cycle analysis : static zone to dynamic zone.

Table 5: Cycle analysis : static zone to dynamic zone.

Travel [No.]	Start time [HH:MM:SS]	End time [HH:MM:SS]	Direction of travel [From→To]	Distance [m]	Haul time [MM:SS]	Return time [MM:SS]	Cycle time [MM:SS]	Unload time [MM:SS]	Load time [MM:SS]	Haul speed [km/h]	Return speed [km/h]
1	08:54:17 AM	08:57:03 AM	Gravel→3	112.43	02:46		05:38		-	2.45	
	08:58:28 AM	08:59:17 AM	Gravel←3	80.79		00:49		01:25			5.94
2	08:59:55 AM	09:00:48 AM	Gravel→3	78.37	00:53		04:22		00:38	5.33	
	09:00:52 AM	09:01:42 AM	Gravel←3	84.51		00:50		00:04			6.08
	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
20	09:52:22 AM	09:53:20 AM	Gravel→3	95.19	00:58		05:11		01:34	5.90	
	09:53:24 AM	09:54:09 AM	Gravel←3	99.82		00:45		00:04			7.99
21	09:57:33 AM	09:58:16 AM	Gravel→3	97.74	00:43		-		03:24	8.17	
	09:58:20 AM	09:59:19 AM	Gravel←3	101.75		00:59		00:04			6.19
			Min		00:25	00:05	01:55	00:01	00:36	1.30	4.18
			Max		03:10	00:59	05:38	01:50	03:24	10.19	13.93
			Average		00:58	00:38	03:10	00:19	01:13	6.59	7.67

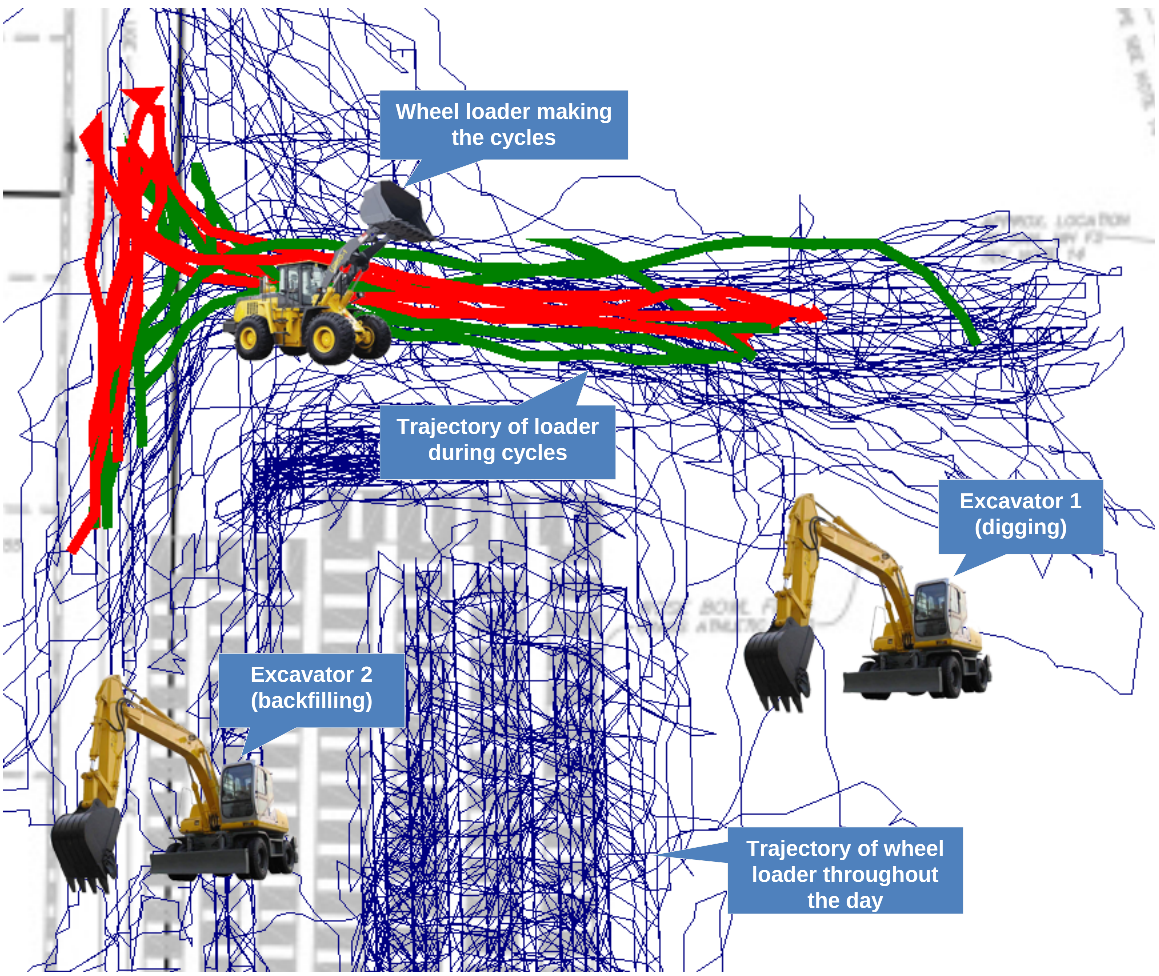


Figure 38: Cycle analysis : dynamic zone to dynamic zone.

Table 6: Cycle analysis : dynamic zone to dynamic zone.

Travel [No.]	Start time [HH:MM:SS]	End time [HH:MM:SS]	Direction of travel [From→To]	Distance [m]	Haul time [MM:SS]	Return time [MM:SS]	Cycle time [MM:SS]	Unload time [MM:SS]	Load time [MM:SS]	Haul speed [km/h]	Return speed [km/h]
1	01:50:37 PM	01:51:05 PM	4→2	52.61	00:28		01:30		-	6.77	
	01:51:14 PM	01:51:41 PM	4←2	60.76		00:27		00:09			8.10
2	01:52:07 PM	01:52:40 PM	4→2	49.14	00:33		01:32		00:26	5.36	
	01:52:45 PM	01:53:14 PM	4←2	57.64		00:29		00:05			7.16
3	01:53:39 PM	01:54:09 PM	4→2	50.29	00:30		02:00		00:25	6.05	
	01:54:18 PM	01:54:47 PM	4←2	53.37		00:29		00:09			6.62
4	01:55:39 PM	01:56:02 PM	4→2	42.57	00:23		01:55		00:52	6.66	
	01:56:07 PM	01:56:31 PM	4←2	55.44		00:24		00:05			8.32
5	01:57:34 PM	01:57:54 PM	4→2	47.18	00:20		-		01:03	8.50	
	01:58:01 PM	01:58:21 PM	4←2	54.65		00:20		00:07			9.83
			Average		00:27	00:26	01:44	00:07	00:42	6.66	7.99
			Max		00:33	00:29	02:00	00:09	01:03	8.50	9.83
			Min		00:20	00:20	01:30	00:05	00:25	5.36	6.62

the travel segment was short. The average cycle time was 1 minute and 44 seconds. The loading and unloading times were found to be 42 and seconds respectively. The loading time is likely to be higher than normal since the loader had to wait for the excavator to pile up the earth and load it, while unloading did not require any preparation time for the wheel loader.

4.4.2 Zone and Speed Analysis

The following scenario presents the analysis of a skid steer loader during the course of a work day. Data from a total of 11 hours and 59 minutes was available (from 08:02:59 A.M. to 08:01:58 P.M.). Figure 39 illustrates the different work zones and grey-shaded trajectories of a skid steer loader. The results are summarized in Table 7 and Table 8.

Table 7 shows that the skid steer loader spent 8 hours in the work zone, 1 hour

Table 7: Summary of zone analysis.

Type of Zone	Entries in zone [No.]	Time spent in zone [HH:MM:SS]
Work Zone	**10**	**08:03:15**
Parking Zone	**4**	**01:33:12**
Other than work and parking Zone(s)		**02:22:33**
Total time		**11:59:00**

and 33 minutes in a parking zone, and 2 hours and 22 minutes in other zones. The time spent in the work zones indicates only that the skid steer was in the working area. This does not imply that the equipment was actually being utilized. Hence, further analysis determined the amount of time it was actually in motion.

Table 8 shows that the skid steer was stationary for 9 hours and 26 minutes during the 12-our work day (or 79% of the total day). Out of the 8 hours the skid steer loader spent inside the work zone, for 5 hours and 50 minutes (or 73% of the time spent inside the work zone) it was not moving.

Similar analysis was done for speed ranging from 0-2 km/h, 2-5 km/h, 5-10 km/h and more than 10 km/h. This evaluation was done to compare the proportion of the time the skid steer loader traveled inside and outside the working zone. The data shows that it traveled at the speed of 0-2 km/h 4% of the entire work day and 5% of the time when it was inside the working zone. The same analysis was done for travel speeds between 2 and 5 km/h, 5 and 10 km/h, and greater than 10 km/h. The results can be read in Table 8. The results show that the proportion of speed distribution at which the equipment traveled inside or outside the working zone was not significantly different.

4.4.3 Proximity Incidents Analysis

Table 9 shows the result regarding the proximity of the skid steer and the excavator for an entire day. The same 12-hour dataset was used for the analysis. The results show

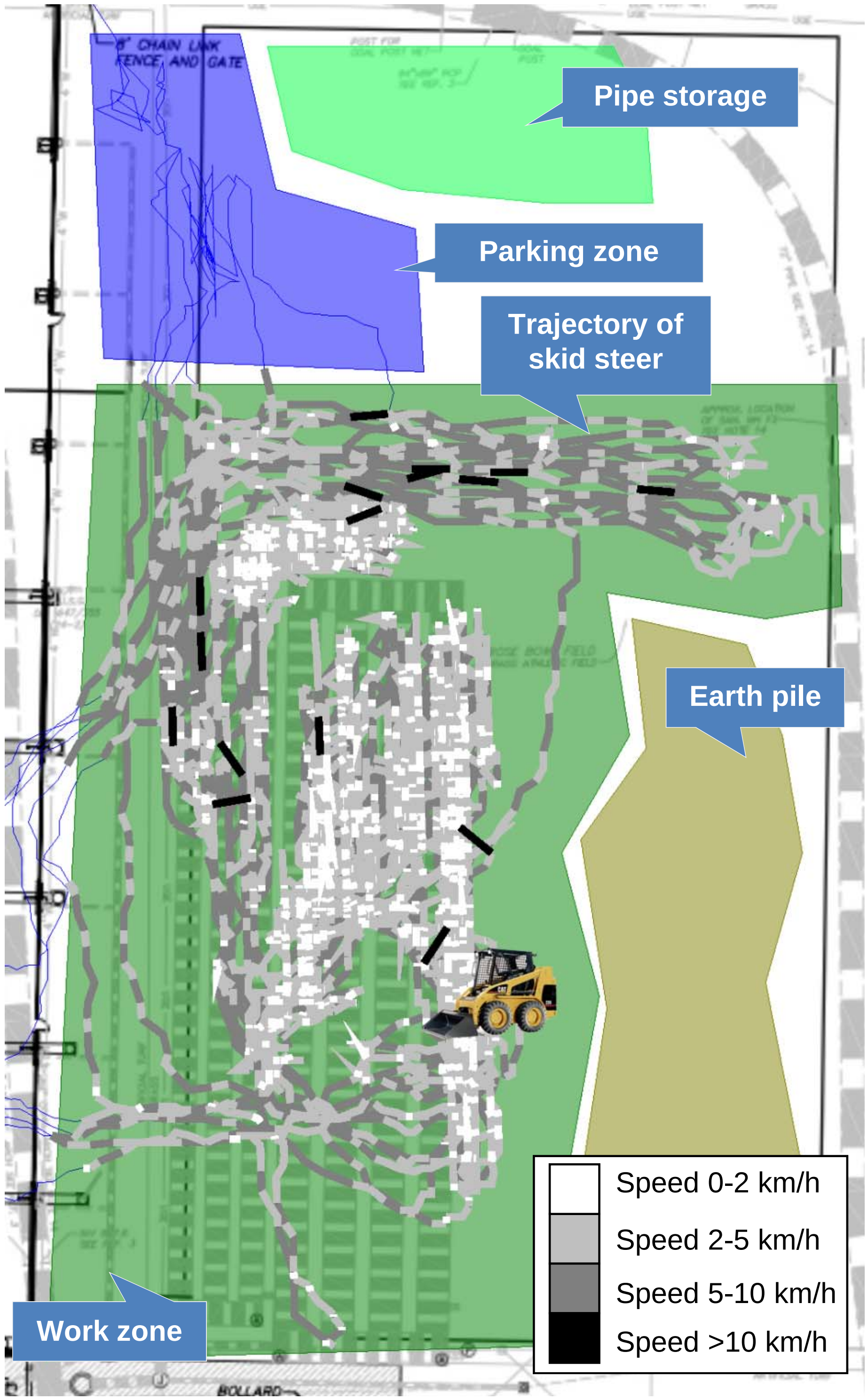


Figure 39: Zone and speed analysis.

Table 8: Summary of speed analysis.

Velocity [km/h]	**All day**		**Work Zone**	
	Time [HH:MM:SS]	**% of time**	**Time [HH:MM:SS]**	**% of time**
0	**09:25:55**	**78.7**	**05:49:45**	**72.4**
0 - 2	**00:27:23**	**3.8**	**00:24:49**	**5.1**
2 - 5	**01:20:08**	**11.1**	**01:09:53**	**14.4**
5 - 10	**00:45:09**	**6.3**	**00:38:32**	**8.0**
$\geq$ 10	**00:00:24**	**0.1**	**00:00:16**	**0.1**
Total	**11:58:59**	**100.00**	**08:03:15**	**100.00**

Table 9: Proximity analysis between skid steer and excavator (threshold = 10m).

Occurrence of less than 10m [No.]	**Start time [HH:MM:SS]**	**End time [HH:MM:SS]**	**Closest distance [m]**	**Closest distance at time [HH:MM:SS]**
1	**08:11:02 AM**	**08:11:14 AM**	**2.24**	**08:11:10 AM**
2	**11:18:27 AM**	**11:18:33 AM**	**8.90**	**11:18:31AM**
3	**01:14:51 PM**	**01:15:30 PM**	**5.07**	**01:15:01 PM**
.....	.....	.....	.....	.....
.....	.....	.....	.....	.....
119	**05:59:56 PM**	**06:00:11 PM**	**3.55**	**06:00:02 PM**
120	**06:14:32 PM**	**06:40:28 PM**	**8.84**	**06:40:28 PM**
121	**06:48:17 PM**	**06:48:46 PM**	**3.01**	**06:48:39 PM**
122	**07:31:06 PM**	**07:36:54 PM**	**6.39**	**07:36:42 PM**

that the skid steer loader and the excavator came in close proximity to each other (less than 10 m) in 122 cases. Further speed analysis resulted in information that the skid steer loader was in motion for 2 hours and 33 minutes on that work day and that the skid steer loader spent approximately an hour (54 minutes and 46 seconds) near the excavator. The minimum distance between the skid steer and the excavator was measured at 2.24 m at 8:11:10 A.M. Adding potential GPS measurement errors may increase/decrease this distance.

4.5 Verification and Reporting

This chapter proposed the development of a platform that can analyze job site operations for productivity and safety. The results were verified with site notes, site pictures, and by manual calculations that were based on video recordings. Cycles were also verified by manual observations and use of the animation pane in the developed platform. It should be noted that the haul, return, load, and unload time in the cycles depended upon the zones, which were manually set by the authors. Although the results may vary based on the geometry of the zones and thresholds defined by a user, any user with knowledge of a job site layout should be able to use the developed platform (Figure 33).

4.6 Summary

This chapter presented the use of low-cost, easy-to-install GPS data logging technology for tracking and analyzing the construction site operation of equipment resources. The developed approach presented a platform that can convert any raw spatio-temporal data into valuable information that construction managers like to use to plan, manage, and control construction site equipment operations. The findings of this work include several case studies on how this kind of data from such inexpensive continuous spatio-temporal data gathering devices can be collected and analyzed.

Specifically, a platform was created that allows effective GPS data visualization. Results from the data of equipment cycles were collected and analyzed. Additionally, equipment locations and speed were analyzed to determine the proximity of the pieces of equipment to each other. Based on the findings, information can be gathered to better organize job site layouts, understand equipment operation and utilization, and prevent hazards on a job site. Future work is necessary to develop a breadth of criteria that will make possible the reliable analysis of location tracking data. Further applications need to be developed, ones that allow decision makers at all levels in construction to take advantage of the knowledge that is built upon the information that can be gathered. It is expected that education and training tools will result from this work, which can greatly advance the field of site preparation, planning, and controlling, including pre-task work planning and job site safety analysis.

CHAPTER V

CELL-BASED SIMULATION MODEL

A cell-based simulation engine was developed from the scratch for this research. This chapter presents the process of development of such an engine in the context of an earthmoving operation. It also presents a framework for automatically integrating real data from the site into a simulation model.

5.1 Introduction

A typical construction operation is repetitive in nature and activities are generally performed in cycles. Hence, Activity Cycle Diagram (ACD) based simulation models are common in the construction industry. Event generation mechanism in an ACD is based on activity scanning in each instance. The CYClic Operations NEtwork (CYCLONE) model was developed by Halpin [56] in 1977 especially focusing on typical cyclic construction operations. State and Resource Based Simulation of Construction Processes (STROBOSCOPE) [86] represents a newer generation system for construction simulation based on ACDs. Other tools like Simphony [54] have been developed, focusing on special purpose simulation. These systems provide services that developers can use to control different system behaviors and also provide platforms for the graphical representation of operations, animations and statistical tools for input and output data. Templates provided for different construction operations can be used as building blocks for new simulation systems. However, these systems do not consider spatial constraints or spatial interactions among resources, which are crucial factors in resource optimization. In order to overcome this, Kamat and Martinez [71] created a system coupling ACD based simulation with 3D visualization to detect potential hazards. The process was to use the results of ACD based simulations visualize operations. Although basic spatial reference was introduced into the simulation, the system could not handle space optimization problems.

Another approach of simulating a model is to build complex systems using Cellular Automata (CA). The concept was developed in the 1940s [88]. A theory for Discrete-Event systems Specification (DEVS) was defined by Zeigler [132] as a formal method for building models in a hierarchical and modular approach. This method is based on a cell space model consisting of an infinite set of geometrically defined cells. Each cell can have many layers corresponding to the attributes that the cell might have. The behaviors of the cells depend upon the state of neighbor cells in the system. The cell-based approach was further explored by Wainer [125] for the development of Cell-DEVS. This approach considered cell spaces as discrete event models and allowed easier ways to model a complex system. A toolkit called CD++ was developed based on this approach and has already been implemented in different types of applications.

CA has been used to model and solve problems in a wide variety of science fields [130]. CA has been applied in developing games [93], parallel computing and nanometer-scale classical computing [9], modeling physical and biological systems in nature [118], social sciences [6], and music [19]. In the context of civil engineering, CA has been successfully implemented in structure analysis and design [87], traffic modeling and control [47] [109], water distribution systems [73], and environmental and urban planning models [79].The use of cell-based simulation in construction operations is relatively new. Zhang et al. [133] implemented a cell-based modeling approach for spatially distributed resources in a construction site. Zhang et al. [133] described steps for creating a cell-based model and demonstrated a case study of a bridge re-decking process. The case study involved removing old sections and installing new panels. The feasibility of the approach was tested for construction environments by comparing the results to those obtained from MicroCYCLONE. Hammad and Zhang

[57] introduced a method of construction equipment collision detection by feeding real-time data into a simulation model. The objective was to overcome the drawback of traditional simulation modeling that used historical statistical data instead of real data from the site. Two radio controlled hydraulic crane models scaled 1:18 were tagged with UWB for a feasibility study. The research concluded that spatio-temporal representation of resources enhances safety analysis and that by feeding real-time data into a simulation model, model adjustment can reflect the real work environment.

5.2 Project Description

For this project, the system under investigation (SUI) is a construction operation involving earth moving activity. A typical earthmoving operation involves excavation, hauling dirt, and piling up the dirt at a different site. For this project, the excavation site was modeled and the activities occurring at an excavation pit were scrutinized. The different entities involved in the SUI are described below.

5.2.1 Site

The Engineered Biosystems Building (EBB) site described in Chapter 3.4.1 was the source of data for this SUI.

5.2.2 Resources

Resources considered in the construction site were the equipment, workers, materials and space. For this simulation, the equipment involved in the earthmoving operation were assessed and a number of “Excavators” and “Dump trucks” were selected as the prime focus of this simulation model. Workers were involved, but their prime duty was only to coordinate the operation.They were not directly involved in the operation. The operation involves dirt as a material. For the simulation, an unlimited availability of dirt is assumed. Space will be considered as a resource that is used by other resources and will be optimized. The number of excavators varied between one and two on a daily basis. The number of dump trucks ranged from 10 to 20 on a given day. The capacity of each truck is 12 cubic yards (CY). The bucket of an excavator can hold 2 CY of dirt when the load was flush to the buckets sides. However, it is usual that more than 2 CY is loaded in one swing by loading a heaped bucket.

5.2.3 Construction Operation

As discussed in Chapter 4, an earthmoving operation consists of four major activities, namely, "Loading", "Hauling", "Unloading" and "Returning". In this particular case, loading involves the excavator making swings to fill the bucket and pour the dirt into the truck to load it. A swing involves filling the bucket with the dirt from the site and dumping it onto the truck. Hauling involves the movement of the dump truck from the point where it gets loaded by an excavator to the point where it unloads the dirt. Unloading involves the truck unloading its dirt at the dump site and returning to the excavator for the next trip, which is "Returning". Figure 40 shows three of these four activities (returning, loading and hauling) in the actual site under consideration. The unloading activity has not been considered for this project because in this case, the unloading occurs outside the local work zone. The same trucks repeatedly perform the operation throughout the day.

5.2.4 Dataset

GPS data loggers were attached to the excavators throughout the day. For trucks, a GPS data logger was attached to the trucks at the entry point of the site and removed at the exit point. Data were recorded for the entire operation and downloaded at the end of each working day. The frequency of data collection was 1 Hz. Only those activities that occurred inside the construction site were considered for analysis. This means that only the parts of the hauling and returning activities that lie inside the site were considered for simulation. The crew started working at around 6:30 AM

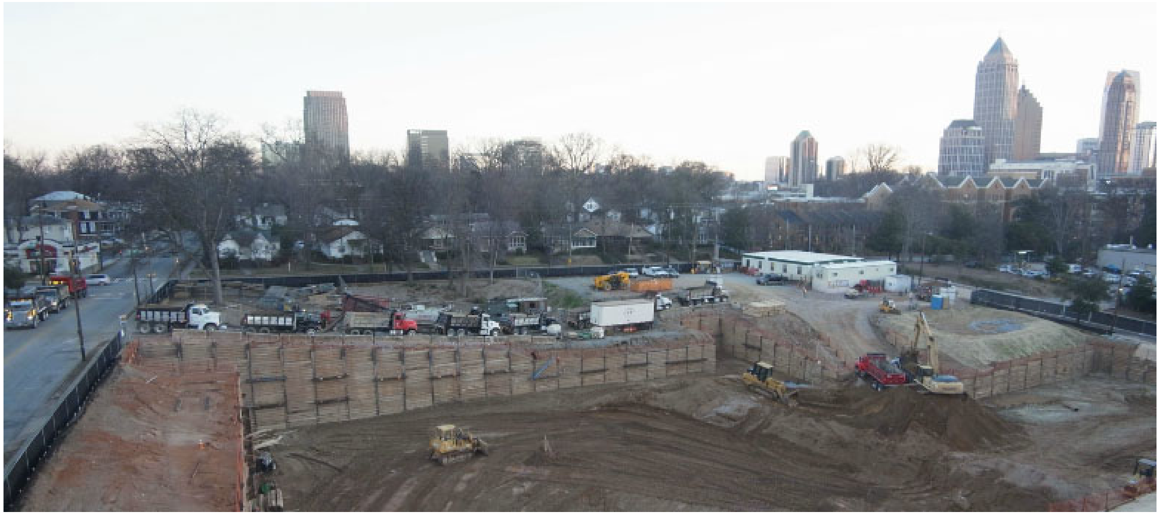
Figure 40: A typical loading activity.

and stopped at around 5:30 PM.

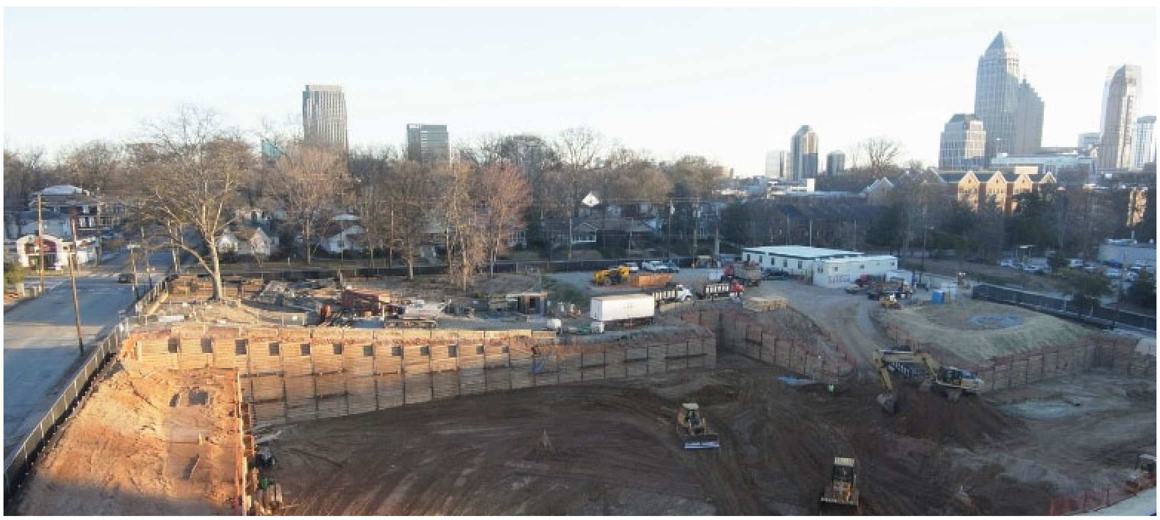
5.2.5 Problem

Like any other production systems, the SUI also operates under cost and schedule constraints. Optimal usage of the available resources is desired to maximize productivity and save costs. Resource optimization is a major concern in Construction Engineering and Management (CEM). Specifically considering an earthmoving operation, a well-planned number of resources and efficient/careful timing can not only save money but also help in in the timely accomplishment of the project while enhancing site safety conditions. The number of excavators and trucks deployed on site depend upon the production requirement of the day. However, increasing the number of resources does not always result in increased production on a construction site. If there are fewer trucks than the excavators can load at a time, the excavators have to wait for the trucks to arrive. Needless to say the hourly operating cost of excavators makes them the key equipment for optimization. If there are more trucks than the excavators capacity, the trucks will wait for the excavators. Choosing fewer trucks in this case not only saves money but also avoids site congestion since fewer idle trucks will be standing on the driveway. It should be noted that all the movement in and out of a typical construction site happen through a specifically designated path, which often becomes a bottle neck, especially in urban construction sites. In these cases, congestion at the site has and adverse effect on all the activities happening at that site.

Space is a scarce resource in modern construction site. Positioning of operations and crews can significantly boost productivity and safety conditions on site. For an earthmoving operation, all the trucks have to move into the excavation pit to the excavator and back outside the pit. Hence, positioning the excavator at optimal locations is also equally important. Last, but not the least, if the interarrival times of the trucks are not regulated, many trucks may arrive at one time, as a result, leaving the site at nearly same time. In this case, even though the numbers of resources are optimized, due to improper time regulation, the site will suffer overcrowding and undercrowding repeatedly throughout the day, seriously hampering overall site productivity. Figure 41a shows the construction site at 7:22 AM. It can be seen that the trucks have queued up outside the site because of a lack of space on the driveway. Figure 41b shows the site on the same day at 7:47 AM, when it seems that the site is waiting for the next arrival. Since it is a cyclic process, once it occurs, this condition will typically persist throughout the day.



(a) Trucks queuing up in and outside the site at 7:22 AM



(b) Site on the same day after 25 minutes at 7:47 AM

Figure 41: Overcrowding and undercrowding on site despite optimal number of resources.

5.3 Methodology

Like any system, the developed simulation system also consists of three components: the input, the simulation engine and the output. Each part is discussed in detail in the following sections.

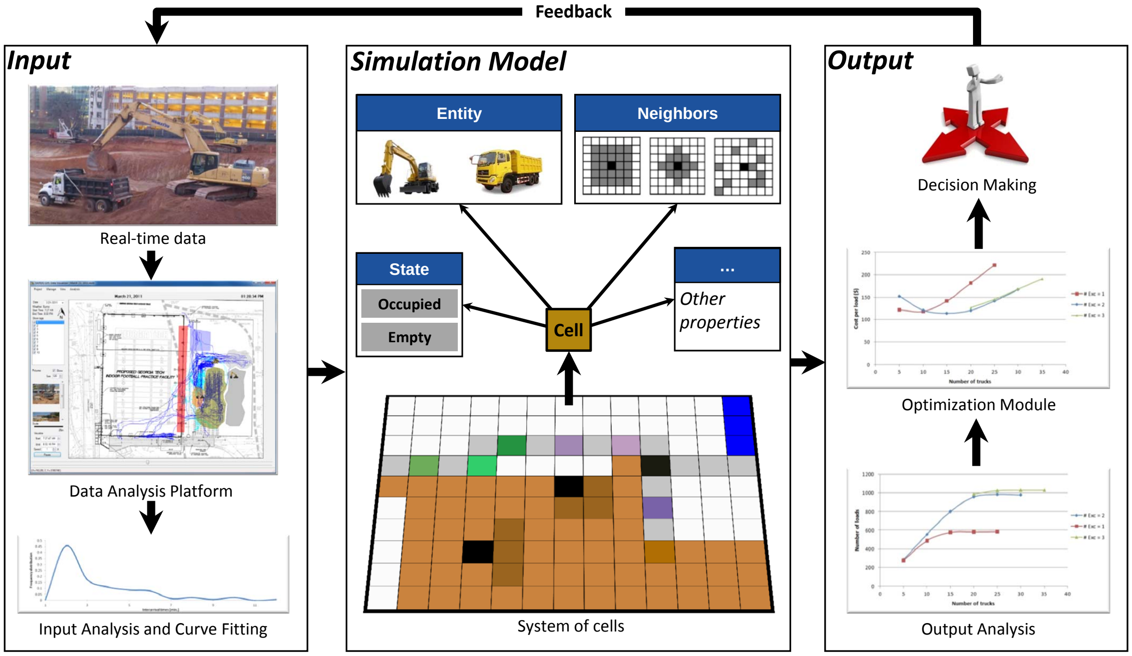


Figure 42: Working mechanism of the simulation system.

5.4 Input Analysis

Use of the Automated Construction Operation Analysis system described in Chapter 4 determined that 136 loading times were made for 136 loads that day. The loading times were tested for multiple curves using Arena software, and gamma distribution was found to be the best fit. A gamma distribution with a Shape factor of 13.1621 and a Scale factor of 7.5266 was adapted. Figure 45 shows the histogram of loading times and the gamma curve fit the distribution.

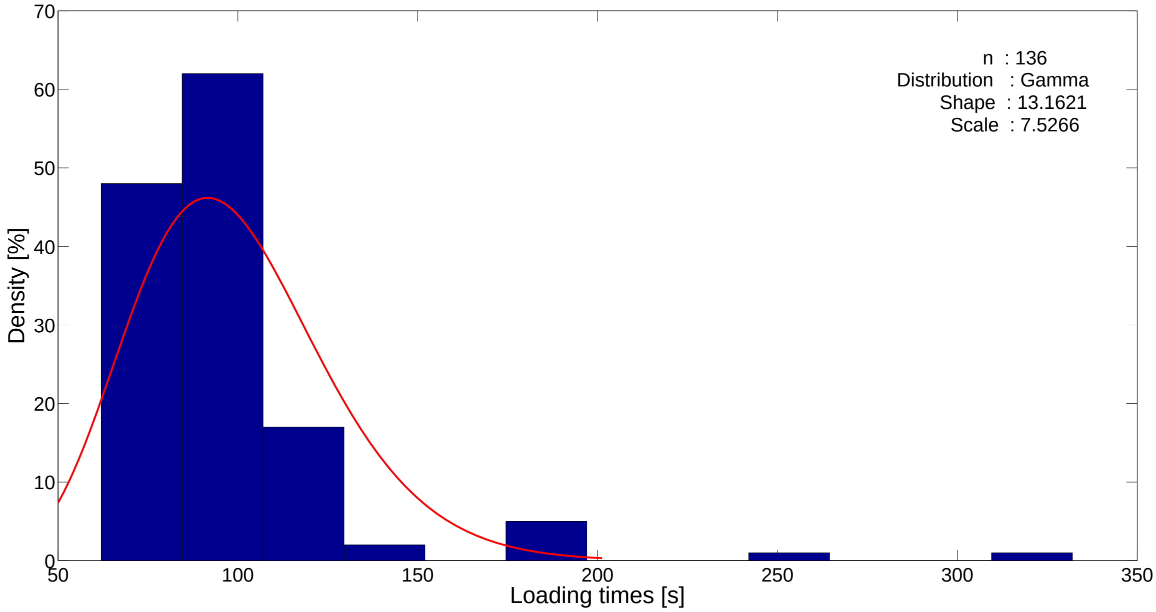
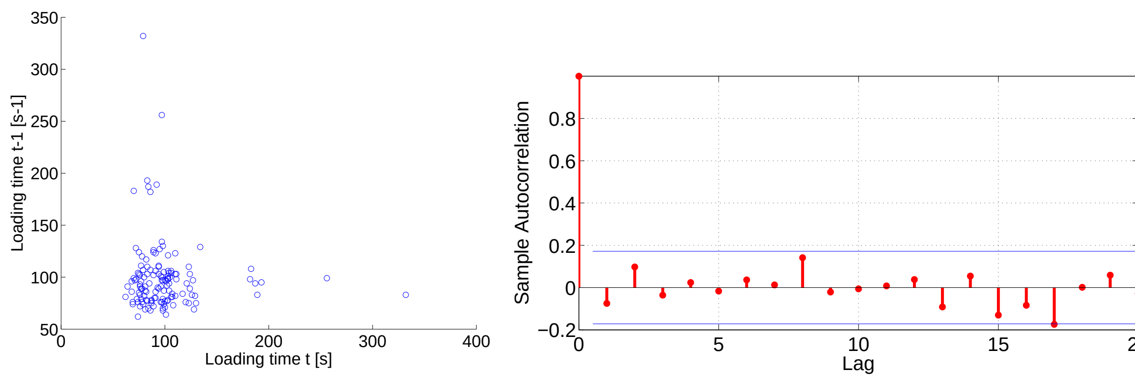


Figure 43: Curve fitting for loading times.

Autocorrelation check was performed for the loading times. Figure 44 shows the autocorrelation plots with one degree of lag (Figure 44a) and with 1 to 20 degrees of lag (44b). There was no significant autocorrelation found in loading times.



(a) Autocorrelation plot (b) Autocorrelation analysis with multiple lags

Figure 44: Autocorrelation analysis of loading times.

One peculiar behavior of the trucks that was observed was that multiple trucks waited at the gate of the construction site before the excavation began. Hence, the initial interarrival times could not be considered for analysis. A total of 125 interarrival times were identified and used for input analysis. A gamma distribution with a Shape factor of 0.8377 and a Scale factor of 320.0542 was fitted to the distribution.

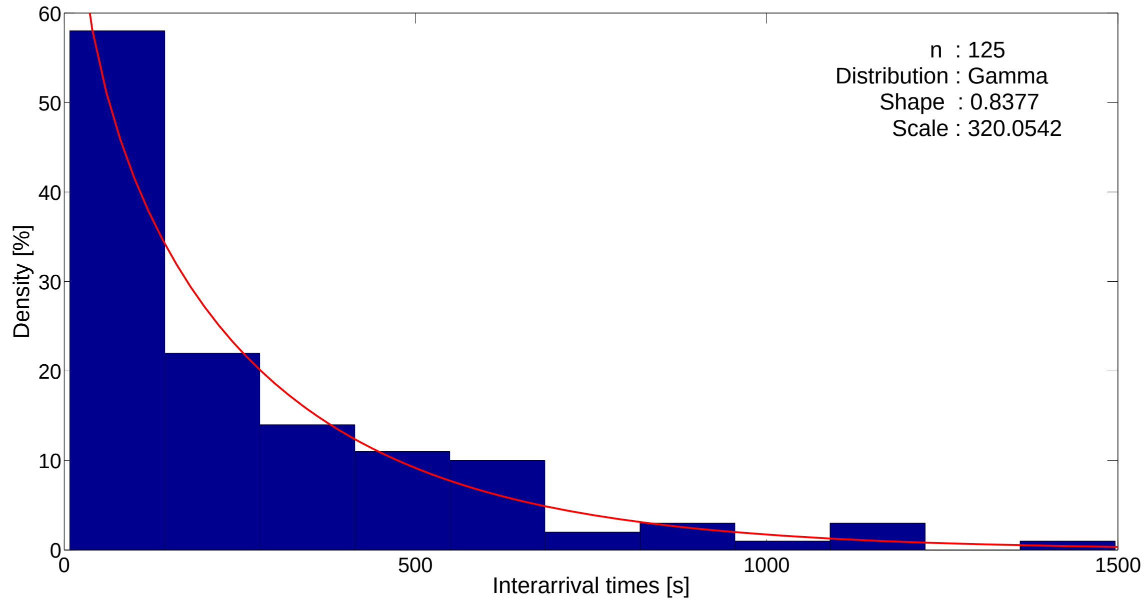
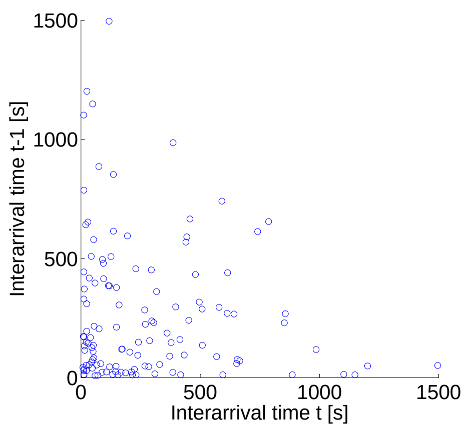
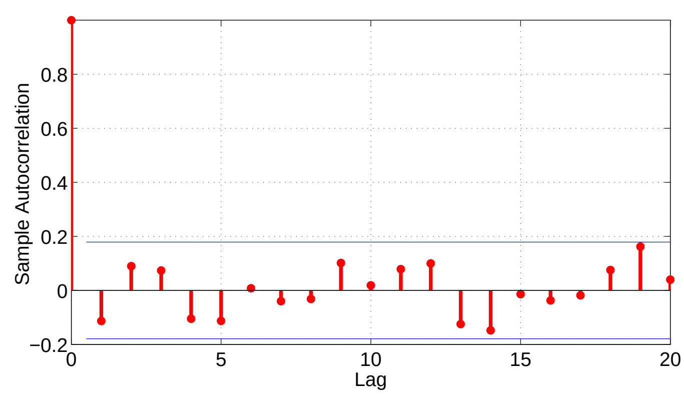


Figure 45: Curve fitting for interarrival times.

Autocorrelation check was performed for the interarrival times but did not yield any significant results. Figure 46 shows the autocorrelation plots.



(a) Autocorrelation plot



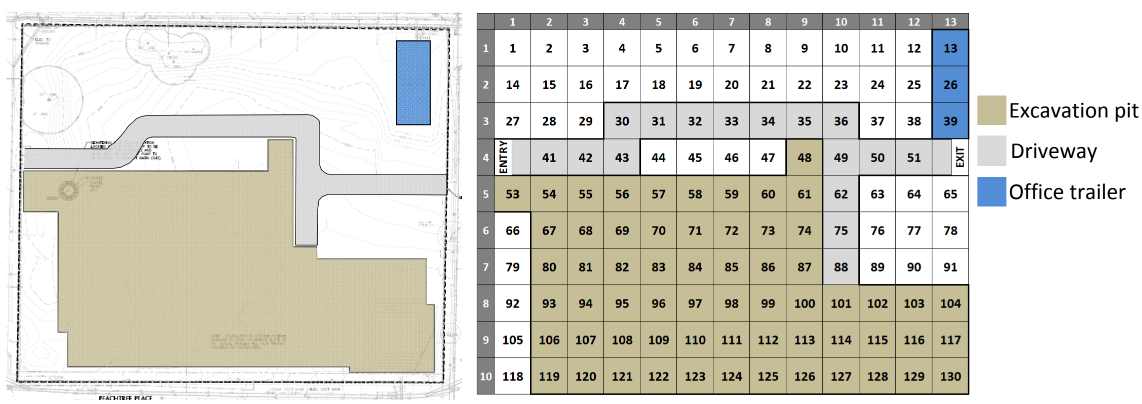
(b) Autocorrelation analysis with multiple lags

Figure 46: Autocorrelation analysis of interarrival times.

Stationarity analysis not performed because the system was assumed to be stationary (in assumptions).

5.5 Simulation Engine

A cell-based simulation based on complex systems was developed from scratch in MATLAB. The properties that a cell needs to hold along with other system properties are explained below in the context of an earthmoving site. Figure 47 shows the cellular layout of the site. A truck was a little more than 8m in length. Hence, the grid size was selected to be $9m \times 9m$, considering the length of the truck and the space between two consecutive trucks. A truck could be represented by a single cell by doing this. Also, the average speed of the trucks on site was 10m/s. Selecting a 9m grid implies that a truck would take roughly 3 seconds (at 10.8 km/hr) to cross a grid. The frequency of one update per 3 seconds could appropriately represent the system. The simulation to be considered was a bound horizon for an 8-hour work day without break.



(a) Site layout map with zones (b) Site divided into cells

Figure 47: Transformation of the site into cell-based system.

In Figure 47b, zones have been marked in different colors. The cells in white represent the part of the site where no activity occurred (those cells never needed to be updated). The trailer area represented the office area and did not need to be updated either. The simulation starts as the truck enters the site through *Cell* 40. Then the truck follows the driveway to *Cell* 36 and proceeds down the ramp to *Cell* 101. From *Cell* 101, the truck would move to the loading area of an excavator and wait for loading. The inter-arrival times of the trucks and the loading times for the excavators are the two stochastic processes in this system. The loaded truck returns to *Cell* 101 and then moves up through the ramp to *Cell* 52, which is the exit. From the exit, an inter-arrival time is assigned to the truck along with a fixed time that it would take to travel to the distant site, unload the dirt, and return to the site through *Cell* 40. The interesting part of the simulation is the ramp that connects the excavation pit to the driveway entering and exiting the system. Only one truck could pass through the ramp at a given time. So, checking only the immediate neighbor could lead to a head-on collision of the trucks on the ramp and result in a deadlock . Details on how movement through the ramp has been handled are described in the following sections.

5.5.1 Objectives

The main objectives of this project are listed below.

- To generate spatio-temporal data from a simulation model based on real-time from a site for a different resource configuration
- To implement a complex systems method for simulating an earthmoving operation using a cell-based model
- To analyze the effect of changing the number of resources (excavators and trucks) on productivity
- To predict the optimum number of resources (excavators and trucks) for a given production volume for a day, using real data from the site by performing sensitivity analysis

5.5.2 Assumptions

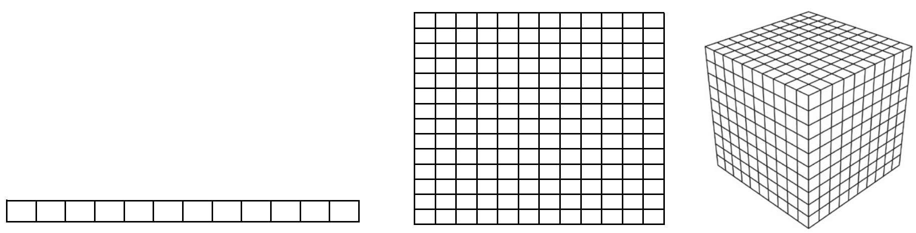
The following assumptions were made for simplification of the system and for construction of the simulation model.

- No other vehicles use the driveway
- No equipment breakdown takes place
- Trucks wait only inside the construction site and their movement is not constrained outside the site
- Trucks do not enter any other part of the site that is not considered in the simulation
- The operation is never disrupted in the middle of the day (due to weather, site issues, etc.)
- No other activities take place in the entire site while the earthmoving operation is in progress
- No activities take place beyond the cellular system outside the site
- All equipment operators are equally skillful
- The external traffic conditions do not affect the interarrival times of trucks (stationary system)
- The excavators can be placed at any point inside the pit without affecting the excavation process (this assumption requires other equipment like dozers and loaders to push earth towards the excavator while the excavator can load the trucks without moving its position throughout the day)
- The trucks travel inside the site through a guided driveway

- The velocity of all the trucks inside the site is uniform
- An unlimited amount of dirt is available

5.5.3 Properties

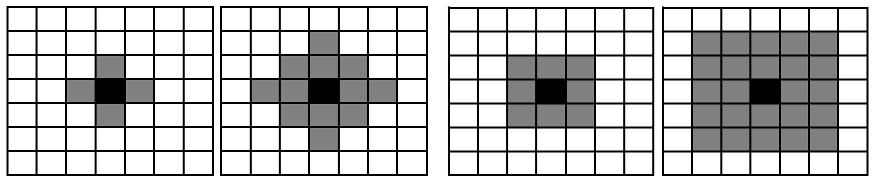
- ***Lattice geometry:*** A two dimensional grid was considered for the system representing the site area and ignoring the elevation difference among parts the site. Figure 48 shows different types of lattice geometry. The elevation difference between the driveway and the excavation pit is covered by the trucks on the ramp. This elevation difference has not been included for simplification of the simulation model because it does not alter the movement behavior of the resources. In cases where a three dimensional simulation model is desired, a 3D lattice should be adapted. An example of such a case would be the erection of a multi-story building.



(a) 1 dimensional (b) 2 dimensional (c) 3 dimensional

Figure 48: Lattice geometry.

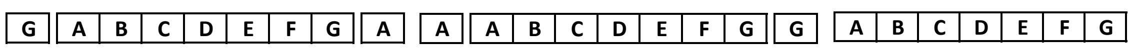
- ***Neighborhood size:*** Figure 49 shows the various types of neighborhoods. In this system, a von Neumann (Figure 49a) neighborhood was assigned to the cells on the driveway to prevent trucks from passing each other on the driveway. The use of a von Neumann neighborhood prevented a truck from being able to move diagonally, which would have restricted the trucks from passing the trucks at the turns in case the cell containing the later truck was updated before the cell containing the previous truck. A Moore neighborhood (Figure 49b) was assigned to cells in the excavation pit to allow free movement in the absence of dedicated lanes. For exceptional cells that controlled the flow of trucks from one zone to another, an arbitrary neighborhood was implemented.



(a) Von Neumann (b) Moore

Figure 49: Neighborhood types.

- ***Boundary conditions:*** A fixed value boundary condition (Figure 50c) best represented the site conditions. Periodic (Figure 50a) or reflective (Figure 50b) boundaries extend the boundary beyond the site which was not desired.



(a) Periodic (b) Reflective (c) Fixed value

Figure 50: Boundary conditions.

- ***State set:*** The state of a cell was labeled 0 if it was unoccupied and 1 or 2 if it was occupied by a truck or an excavator at a given time.

- ***Initial conditions:*** The information about the zones in which the cells lie was provided through a csv file. The zones included 0 for cell not considered for any activity, 1 for the driveway, 2 for the excavation pit, 3 for the loading area of the excavator, and 4 for the trailer. Similarly, the positions of the excavator and corresponding loading area were also fed into the system through a csv file during initialization.

- ***Transition rules:*** Instead of direct specification or probabilistic rules, a multi-step transition rule based system was adopted. This means that different ranges of cells would compute different parameters before making the next move. The algorithm followed for transition rules is shown in Figure 51.

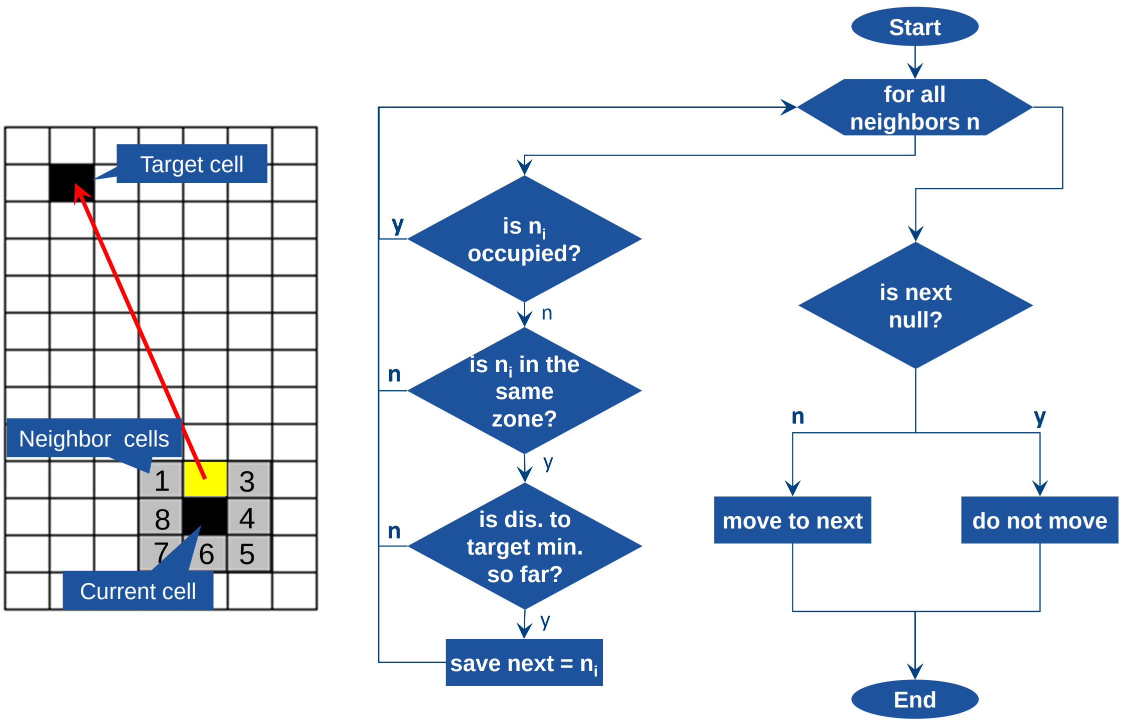


Figure 51: Algorithm defining transition rules.

The algorithm loops through all the neighbors of the cell under consideration. Each cell is assigned to a target cell to which the movement is directed. For each neighbor of that cell, an occupancy test is performed to assess if the cell is willing to welcome any occupant. If the cell is available, a zone test is performed on the cell to confirm that the movement would be constrained to the same zone. Now, the cells passing both these tests are compared for distance to the target cell. A movement is made only if moving to that cell reduces the distance towards the target.

Figure 52 shows the trajectory that a truck follows in the system. *Cell* 36 and *Cell* 101 are controlling cells and are governed by special transition rules.

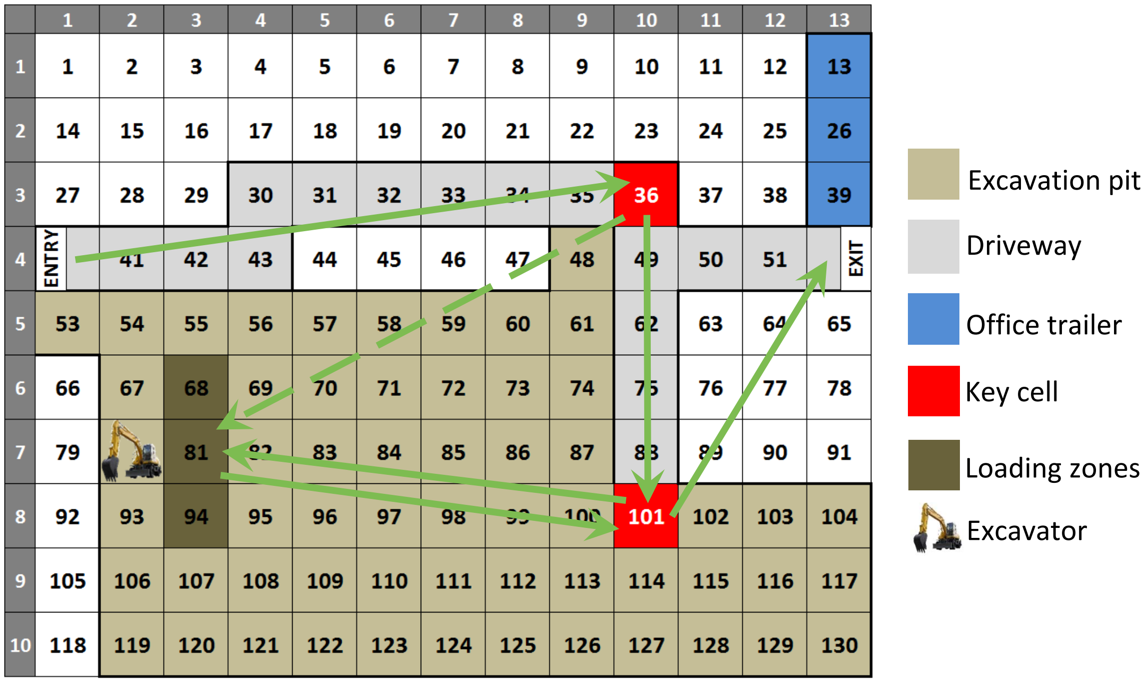


Figure 52: Grid system with transit points.

Following is a description of what happens at key cells in the system.

Cell 40: Truck enters the system. *Cell* 36 is assigned as the target cell.

Cell 36: This cell checks if any loading area is available around any excavator in the pit. If yes, it will check if any loaded truck is still in the pit. If a loading truck is there, it might block the ramp in the future . If no loaded trucks are inside the pit, *Cell* 36 checks if any loaded trucks are already on the ramp. If none of the above-mentioned conditions are present, the system will set the trucks target cell to *Cell* 101 and also assign a loading zone to the truck. The loading zone next to the excavator having least number of trucks around it in the given instance is assigned to the truck.

Cell 101: This is the bottle neck cell which has to be passed by both unloaded and loaded trucks. For this reason, before any truck enters this cell, a test makes certain that no cells are currently on the ramp in the opposite direction. The truck may, however, follow another truck moving in the same direction on the ramp.

This cell also exhibits a different rule for loaded and unloaded trucks. If an unloaded truck comes to this cell, the system will redirect it to the loading zone which has been assigned to that truck. If a loaded truck comes to the cell, the cell will forward it to *Cell* 52, which is the exit. This is also the only cell in the system where a truck changes zones (i.e., from driveway zone to pit and back).

Cell 52: This is the exit cell. It assigns the next arrival time for the truck and moves the truck out of the system. The trucks arrive at the entry cell based on the inter-arrival time assigned here.

A copy of previous states of the cell is stored in the memory before the transitions are initialized. This helps if roll-back is necessary at any point. The trucks entering the site first get the priority to move in each instance. Lets say truck A enters the site first, followed by truck B. Then truck A gets the priority to move. This is done because a truck following another truck on a driveway would tend to occupy the cell occupied by the truck before it. If truck B gets priority, the cell before it will be occupied by truck A at the instance truck B tends to move. When truck A is analyzed for transition, it will move forward, leaving its cell for truck B. Truck B might not check the availability of neighbors again at this instance. In this way, prioritizing the trucks by their entry time can prevent most of the conflicts on the driveway. The rule not only prioritizes by entry time but also compares the current state with the previous state of the cell-system. In an instance where truck B gets loaded first, truck A will be behind truck B while exiting the site. In this case, truck A (which is behind) will tend to move first. But truck B is occupying the cell. It does not move. Truck B moves forward. But if the neighbors are now analyzed for the Truck A, it can move too. In this case, the new states of the cell are checked for movement.

5.6 Output Analysis

The first advantage of implementing a cell-based system is that it can be visualized directly without any further processing. Figure 53 shows am instance of visualization. Figure 53 also shows that the location of the trucks in each instance is known and can be saved so as to generate spatio-temporal data from the simulation. The utilization of such generated data is discussed in Chapter 6.

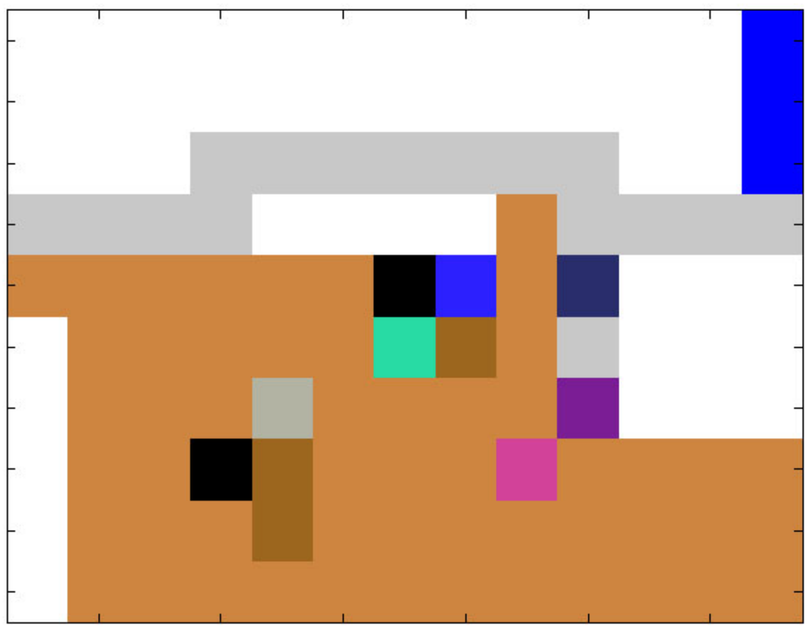


Figure 53: Simulation visualization in MATLAB.

Like traditional simulation models, cell-based models are also capable of performing sensitivity analysis for varying number of resources on the site. Figure 54 shows the results of simulating the system for one and two excavators for multiple trucks. Each point in the chart represents the result of 50 runs of simulation. It can be observed that the curve flattens at a point and remains stagnant. This is because the production capacity of the excavators becomes exhausted after there are more trucks on the site than can be loaded. After that, any addition to the number of trucks will not yield additional production.

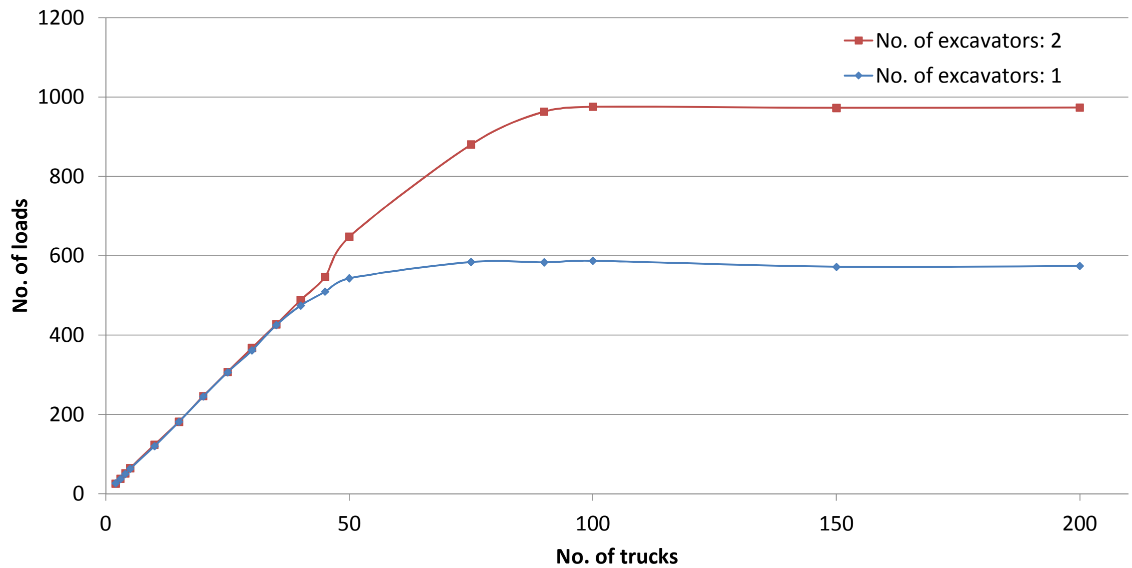


Figure 54: Simulation output for multiple resource configurations.

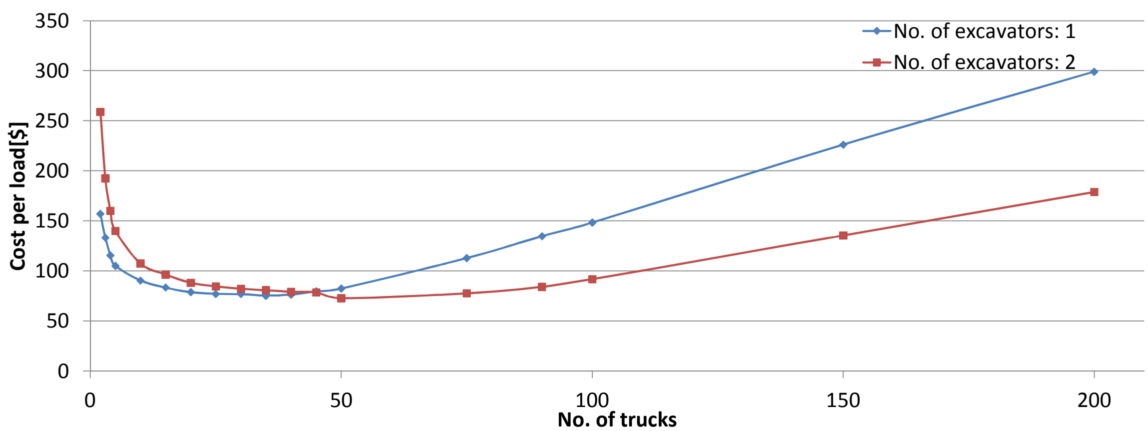


Figure 55: Cost optimization using sensitivity analysis.

This phenomenon of productivity exhaustion can be utilized to optimize the cost of the operation. For instance, it can help to determine the number of excavators and trucks that yield the most production for the same cost/load. Conversely, if a production level needs to be attained, the optimal resource configuration that yields the production level for the lowest cost can also be computed.

Resource optimization is a classic problem that simulation models are used for. This research is not focused on the productivity aspect of the construction. The main objective of simulating a site here is to generate a trajectory of the resources based on collected data.

In this research, the major benefit from implementing a cell-based model is that it is a continuous simulation model and simulates the position of all the resources at each instance. This is not possible in a discrete-event simulation model. Discrete event simulation triggers only when an event occurs at the site.The focus of this research is to analyze the interaction of the resources at each instance. For this reason, cell-based simulation has to be implemented to thoroughly understand the interaction even when no notable event occurs.

5.7 Feedback Loop

The valuable information obtained by simulating the site under different site conditions can be applied in future operations through a feedback loop. New decisions are implemented and real-time data are continuously collected, further enhancing the simulation system and providing better decision making capacity.

5.8 Model Verification

Verification is the process of confirming that the right model has been built for the system. In the case of a cell-based system, since the entire simulation process can be observed visually, checking the model can be done by observing the movement of the entities in the simulation system. In this specific case, the trucks are supposed to arrive at the gate, find their way through the driveway, wait for an empty spot next to nm excavator, wait for the ramp to be empty, wait to be loaded, and then exit through the exit gate. All these activities can be visually verified to check if the model has been built correctly.

One way to verify a system is to compare the output against the output of another established system. In this case, the developed model is verified against EZStrobe [85]. Although the two models are based on completely different philosophies, the outputs should match if they both represent the same site. An equivalent model was

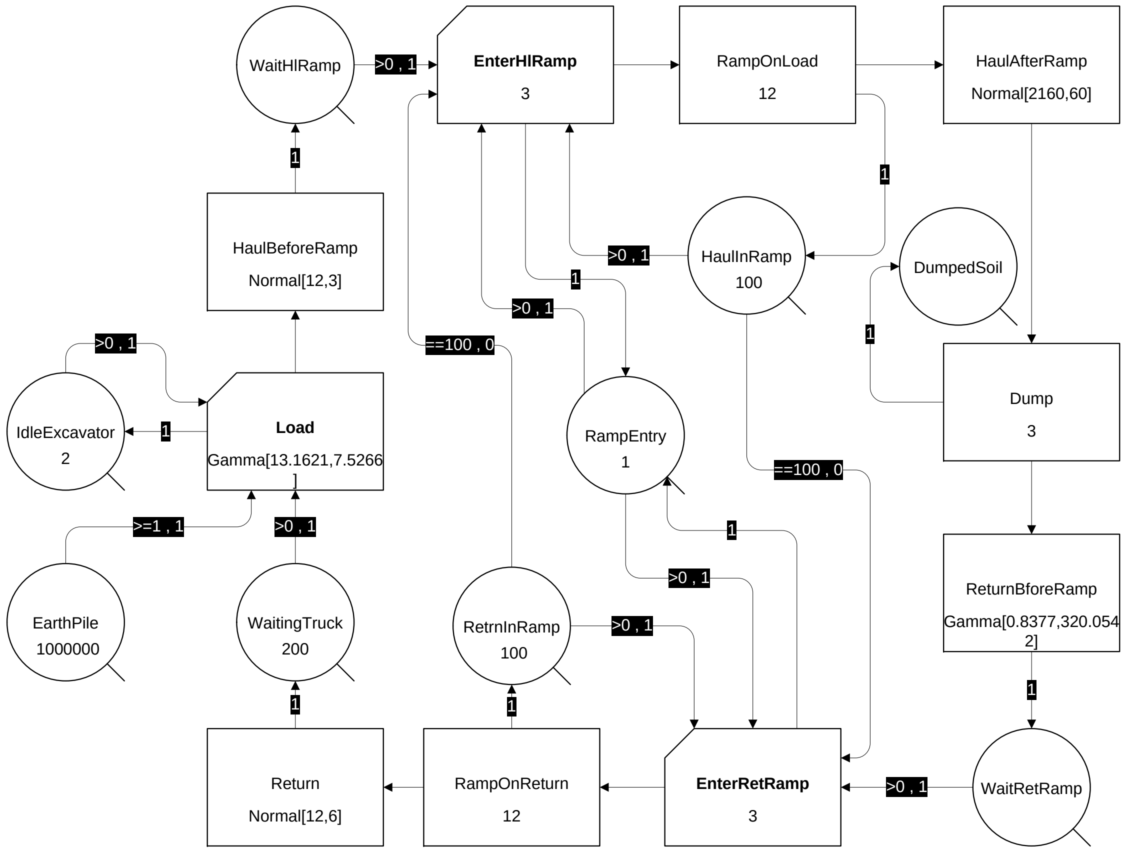


Figure 56: Equivalent model in EZStrobe.

built in EZStrobe. Figure 56 shows an equivalent discrete event simulation model for the same system. Since only two stochastic processes were used in the cell-based model, the results of the two models are not expected to exactly coincide . In the cell-based system, the entities traverse through their neighbor cells and hence activities like returning time and hauling time are handled by the system itself. In the model shown in Figure 56, the nearest possible distribution was assigned to those activities based on manual judgment .

Figure 57 shows the results of verification. It was observed that the two models are comparable with each other in the beginning, but the predicted output from the cell-based model was much more than that predicted by the EZStrobe model. It was also noticed that this deviation occurred near the saturation point for the system,

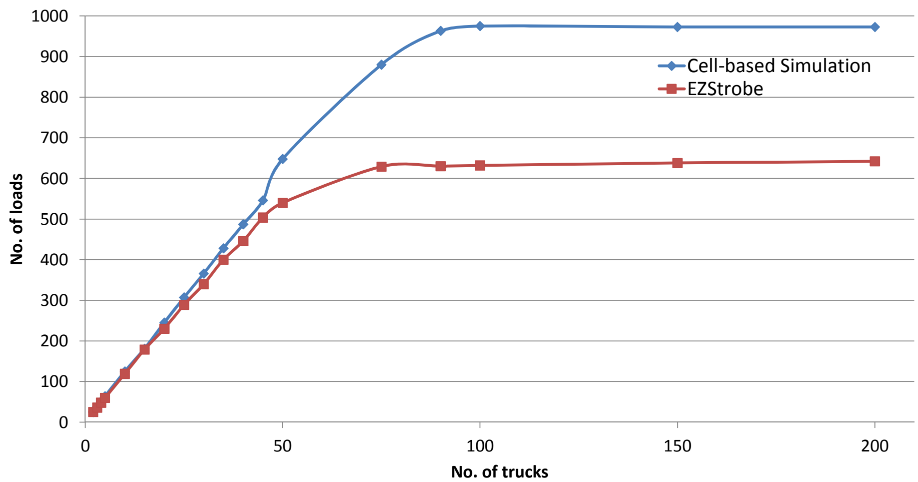


Figure 57: Cross validation with EZStrobe.

where the curve flattens. This discrepancy can be attributed to the assumptions made for the construction of the cell-based model. One of the major assumptions is that all the activities happen inside the site and in the cells. When the number of trucks becomes unrealistically high, some trucks need to line up outside the site. The maximum number of trucks that hauled the earth in this site was 15 to 20 on different days. When 50 trucks are assigned to do the same task, the site becomes insufficient to provide a waiting spot for the trucks. Another difference between the two models is the ramp. The cell-based system allows trucks to follow one another on the ramp as long as the traffic is in one direction. The discrete event simulation limited the mobility of the trucks on the ramp as soon as one truck is on it. This accounts for 12 to 15 seconds delay in a truck's hauling time inside the site. It might not make a significant difference for a small number of loads but can affect the system extensively when the excavator is working at its maximum capacity.

5.9 Conclusions

A cell-based simulation system was developed to model cyclic activities that occur in a construction site. A method of developing cell-based simulation model was described. The capabilities of the system to handle complex system were demonstrated and the parameters of the cells were explained using a case of an earthmoving operation. The advantages of using a cell-based system over a traditional simulation model included easy visualization and simplicity in modeling spatial constraints (e.g.; a ramp restricting the traffic flow to one-way). The system of cells also provided full control over the flow of resources by using predefined rules or algorithms. The cell-based system also simplified the design process since, except for some special key cells, other ordinary cells followed the same rules and did not need to be programmed individually. Implementing real-time data into the simulation and using the feedback loop helped in creating a more realistic model. Future development of this system should include multiple crews competing to share resources when the members of the crew do not interact with each other but share the same workspace. The system has been verified with a discrete event simulation model for one particular site layout. The system needs to be validated for multiple site layout with different resource configurations. Real results from the sites should be used for cross-validating the results obtained from the simulation model to ensure that the engine yields practical results. In terms of safety and the study the interaction among resources, this system offers the advantages of continuous simulation over traditional event-based simulation methods. Continuous simulation generates spatio-temporal data for resources in each instance, which can be analyzed as if it had been collected from a real construction site. For such cases workspace conflicts and the effect of one crew on productivity because of congestion due to other crews can be analyzed. This system will help decision makers make better decisions regarding resource allocation and site layout planning. It can also be used as a training tool to allow project managers to become familiar with the effects of changing resource combinations on site.

CHAPTER VI

AUTOMATED CONSTRUCTION SITE SAFETY HAZARD MAPPING

This chapter presents the method devised for identifying and quantifying at-risk behavior on the site. It identifies the spatio-temporal parameters that affect the safety conditions on site and details a method for accumulating such parameters for a unified scoring system. The chapter also describes a grid-based hazard mapping method and presents a way to identify resources prone to potential hazards.

6.1 Introduction

Hazard mapping is a method of highlighting vulnerable areas on site to draw them to the attention of a safety manager. Such maps are commonly used in natural disasters on a large scale and have the potential of preventing death and damage [121]. In construction research, occupancy grids and time-space conflict have been studied in various ways [115] [5] but they have rarely been explored for mapping safety hazards on site [28]. Mapping has also been used as a visualization technique in asphalt paving operations, where parameters like temperature play a key role [123]. This research deals with leveraging spatio-temporal data from construction resources to map at-risk behaviors on site. This method can be helpful for gathering leading safety indicators and preventing potential injuries and fatalities. This work considers only spatio-temporal issues involved in human-equipment interaction in outdoor construction environment.

As introduced in Section 1.6, multiple parameters responsible for potential hazards may exist on site. A model incorporating those potential parameters can precisely represent the safety conditions on site so that potential hazards can be analyzed accurately. However, not all the parameters might be easy to quantify or even measure. One example of such parameters is human behavior., which has a significant effect on safety or resources but can not be measured or quantified. This research deals only with spatio-temporal parameters, only those parameters that include space and time or being in the "wrong location at the wrong time" are considered. The following sections discusses the parameters that require only location data from the resources.

6.2 Hazard Weighing Parameters

Spatio-temporal data that can be obtained from a single tag placed on a resource can be analyzed for the parameters listed below to assess the potential risk of an instance in time. The basis of the assessment of the severity of the risk can be based on historical data and the considered list of parameters is not exclusive . The weights introduced in each of the parameters will be used in Section 6.3. Each instance in the trajectory of the resources is checked for all these parameters, and a final score is calculated for each instance. This means that if the frequency of data collection is 1Hz, the score is computed each second. The weights assigned are based on historical statistics as far as possible. Since it is not a common practice to gather spatio-temporal data from workers, statistics are not available for all the parameters. In such cases, weights based on best understanding of the site are used.

The weights are assigned in a two-fold manner. For instance, if it is believed that proximity instances are 4 times more frequent than blind spots, the weight with a single subscript (w_i) will be assigned 4 for proximity and 1 for blind spots. The value merely represents the severity, and the magnitude is normalized while computing the total weight. A weight with a double subscript (w_{i_j}) represents the value of the severity of the parameter. For instance, if the front region of the blind spot is 5 times more hazardous than the left side (Figure 59), then, the the left side will get a sub-weight of 1, and the front region will get a sub-weight of 5. This magnitude is also normalized. The second subscript has been represented by k for all parameters as it can take any sub-weight in that parameter.

6.2.1 Blind spot

Statistics from 594 fatalities that occurred between 1990 and 2007 show that 55% of visibility-related accidents were caused by blind spots of the equipment. Figure 58 shows the distribution of fatalities by cause of accidents. Weight assigned to the blind spots will be effective every time a worker passes through the blind spot of a piece of equipment. It is a binary weight and can take a value of 0 or 1. This is a penalty for just being in the blind spot of a piece of equipment.

$$w_{bs} = weight\ assigned\ for\ blind\ spot$$

$$w_{bs_k} = \begin{cases} 0 & \text{if } blind\ spot = false \\ 1 & \text{if } blind\ spot = true \end{cases}$$

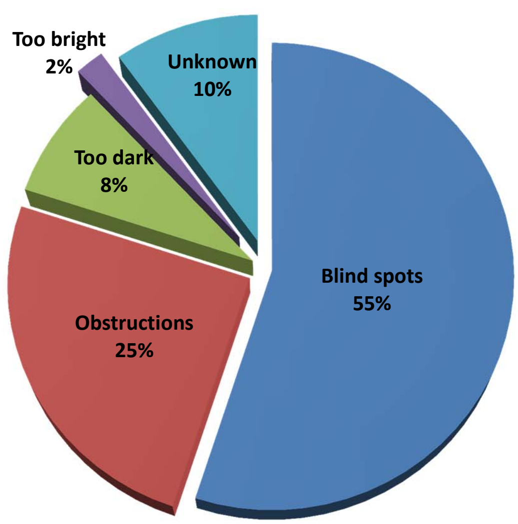


Figure 58: Fatalities categorized by cause (1990-2007,n=594)[68].

6.2.2 Region in Blind spot

Blind spot regions are found to vary from one model of equipment to another [83]. Since the interaction of workers around the equipment is not known, the dominant area of a blind spot can not be identified. Workers might find a potentially hazardous blind spot safe because of their habit of working with a different model of the the same kind of equipment. Also, some equipment can be found to be modified after it is bought. Loads attached to the equipment or moving parts also change a worker's perception of the blind spot of a piece of equipment [104]. Also, all parts of blind spots are not equally hazardous. Figure 59 divides the blind spots of a skid steer loader into eight regions. For a piece of equipment moving in a linear path, the front and back regions might be the most hazardous, followed by the front left, front right, back left, and back right areas. The left and right region might be the least hazardous, assuming the worker is moving parallel to the equipment. If all the regions are assigned the same weight, this is equivalent to the above mentioned case of blind spot.

$$w_{bsr} = weight\ assigned\ for\ blind\ spot\ region$$

$$w_{bsr_k} = weight\ assigned\ for\ particular\ region\ (front, left, right, back, etc.)$$

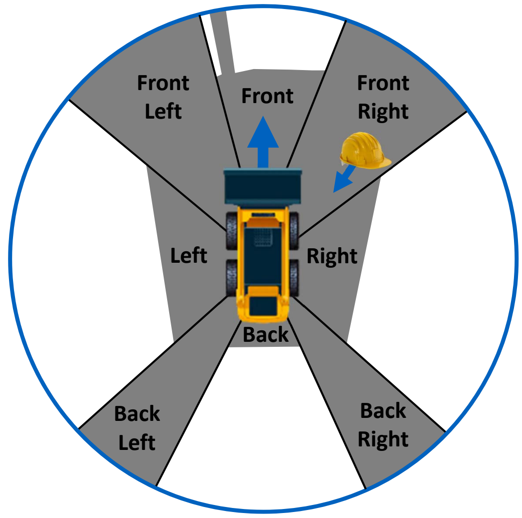


Figure 59: Weight assigned based on region in blind spot.

6.2.3 Proximity Condition

Multiple factors govern the level of a hazard associated with proximity. The velocity of the equipment, the type of the equipment, the kinematic behavior of the equipment, the relative direction of the motion of worker and equipment may may all be factors, to name a few. A circular proximity region is considered around the equipment for analysis. The severity of a hazard does not also linearly vary with the distance between the resources. For the purpose of this research, closer cases of proximity will be assumed to be exponentially at greater risk. An exponential function which flattens at a 12m radius is adapted and the weight for the proximity increases exponentially as it approaches the equipment. It should be noted that the weights give only the degree of severity and do not necessarily predict any incidents. Figure 60 shows an example of such a rule.

$$w_p = weight\ assigned\ for\ proximity\ hazard$$

$$w_{p_k} = e^{-\frac{distance}{2.6}}$$

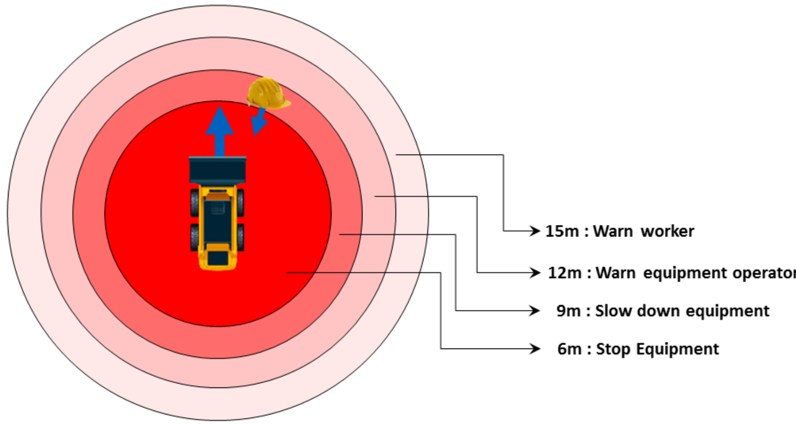


Figure 60: Weight assigned based on proximity condition.

6.2.4 Proximity Region

The region around the equipment where most of the proximity incidents occur is of prime interest for calibrating radio frequency based antennae [82]. The placement of antennae and the direction can change their working range. However, since the devices cannot log the position at which such incidents occur, optimal calibration is normally based upon guesswork. Analyzing the spatio-temporal data of the workers can help document and analyze such incidents to understand the need for coverage of the antennae and calibrate the working range. Being directly in front of a piece of equipment that is moving towards a worker is more hazardous than approaching the equipment from the sides. Such distinctions can be made, and proper weights can be assigned based on the region around the equipment where such incidents occur. Figure 61 shows a polar model of such an analysis.

$$w_{pr} = weight\ assigned\ for\ proximity\ region$$

$$w_{pr_k} = weight\ assigned\ for\ particular\ region$$

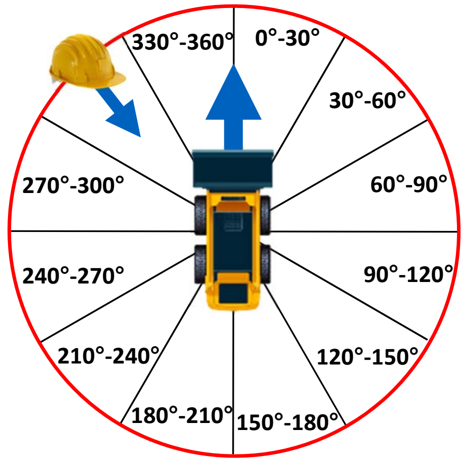


Figure 61: Weight assigned based on proximity area.

6.2.5 Access-controlled Hazard Zone

Another major type of hazard based on location is access controlled zones. A weight can be assigned to the effect of such zones based on the severity of risk that the zone brings in . Different zones might have different levels of risk. Such risks can be reflected in sub-weight under access-controlled hazard zone weight.

$$w_z = weight\ assigned\ for\ access - controlled\ hazard\ zones$$

$$w_{z_k} = weight\ assigned\ for\ a\ particular\ zone$$

6.2.6 Equipment Type

Figure 62 shows that the number of fatalities also depends upon the type of equipment. The equipment that has the potential of creating more hazards should be monitored more carefully than other kinds of equipment. Hence,

$$w_{eq} = weight\ assigned\ for\ equipment\ type$$

$$w_{eq_k} = weight\ assigned\ for\ a\ particular\ equipment$$

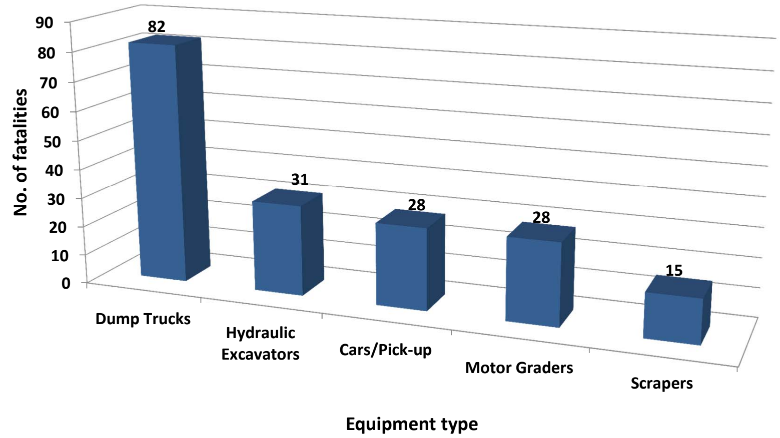


Figure 62: Fatailties categorized by equipment type (1990-2007,n=594)[68].

6.2.7 Time

Time of day is another factor that has been studied for fatalities [68]. Figure 63 shows the distribution of fatalities by time.

$$w_t = weight\ assigned\ for\ time\ of\ day$$

$$w_{t_k} = weight\ assigned\ for\ a\ particular\ time\ period$$

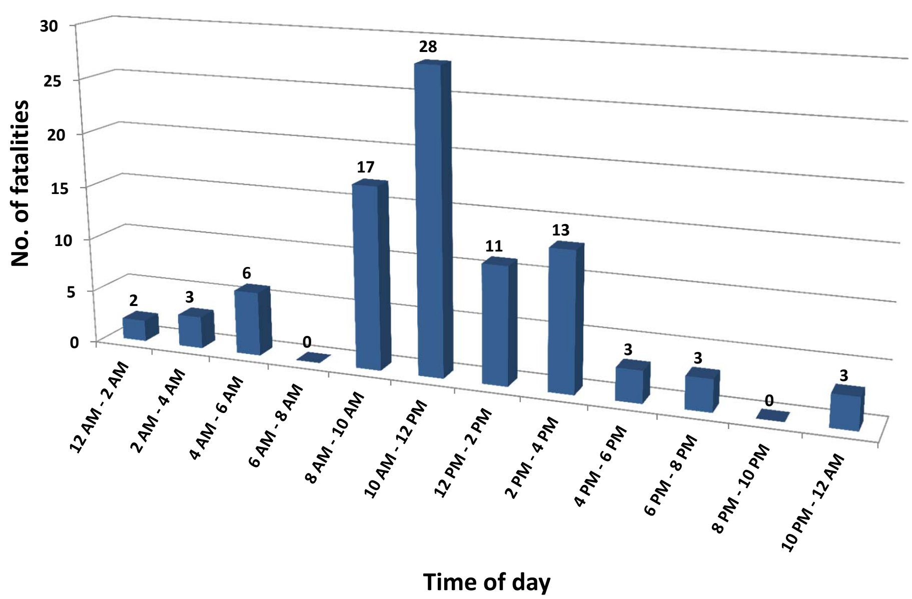


Figure 63: Fatalities categorized by time of day (1990-2007,n=594)[68].

6.2.8 Approach Velocity

The velocity at which the equipment is traveling may affect the severity of the potential hazard . It should be noted that the velocity at which an equipment can travel depends on the type of equipment, model, terrain, loading condition and even location inside the site (driveways might have a higher permissible velocity than an excavation pit). While this parameter has been studied extensively in transportation research [105] [112], statistics pertaining to construction industry is rare to find. For this research, the effect of velocity is not assumed to be linear because higher velocity can potentially have a higher risk of collision as well as a higher degree of damage. A parabolic curve that yields a weight value of 1 at 25 miles/hr is adapted for ease. The weight starts at 0 at 0 miles/hr and rises to 1 at 25 miles/hr parabolically. The velocity of 25 miles/hr is assumed to be the upper threshold inside the site.

$$w_v = weight\ assigned\ for\ approach\ velocity$$

$$w_{v_k} = \frac{velocity^2}{625}$$

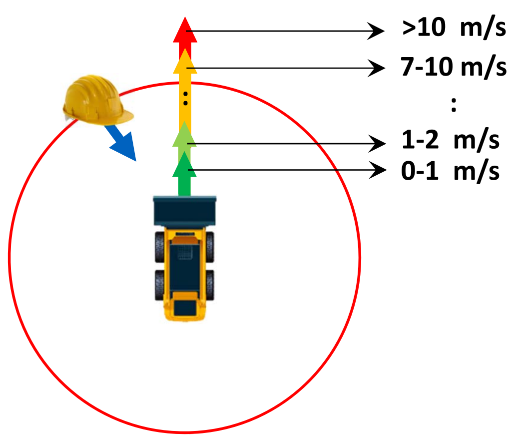


Figure 64: Weight assigned based on approach velocity

6.2.9 Composite Parameters

Composite parameters are combinations of two or more of the above mentioned parameters that, when combined, might result in an instance of severity higher than its components. Some examples are listed below.

- Being in both a blind spot and proximity . Being both in blind spot and proximity at the same time means that the equipment operator cannot see the worker and that the workers is already too close to the equipment. This type of condition is a combination of the presence of two of the above-mentioned parameters. A special weight can be assigned to such instances.

- The resulting approach velocity. Equipment's approach velocity has been discussed above. However, if a worker is moving in a direction away from the equipment, the resultant velocity will not put the worker in a hazardous position.

- Data from more than one sensor on equipment can provide us with the equipment's travel direction. This can act as a valuable parameter for identifying the risk from the motion of the equipment. Figure 65 suggests that more accidents occur when the equipment is traveling in a reverse direction.

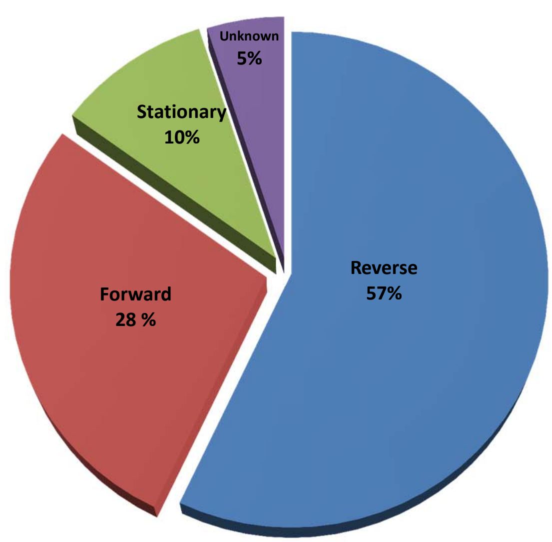


Figure 65: Fatailties categorized by equipment travel direction (1990-2007,n=594)[68].

6.2.10 Other Parameters

Besides the parameters mentioned above, other non spatio-temporal parameters are equally important and have been studied for their influence on safety [66] [61] [8] [24] [53] [68] [104].

- Age of worker
- Size of company
- Environmental factors (Weather, Illumination, Gas/vapor/mist/fume/smoke/dust, working surface)
- Body posture
- Equipment operator's head orientation (Dynamic blind spot)
- Worker's education level
- Material being moved
- Trait or Type of work
- Physiological Status
- Human factors

6.3 Cell Score and Hazard Index

After weights have been assigned to some or all of the parameters, an aggregate cell score can be calculated for each cell on the site. The site is divided into a grid system of fixed square sizes . Each instance occurring inside a cell is identified, and a cell score is computed using the following expression,

$$Cell\ Score =$$

$$w_{bs} \times w_{bs_k} + w_{bsr} \times w_{bsr_k} + w_p \times w_{p_k} + w_{pr} \times w_{pr_k} + w_z \times w_{z_k} + w_{eq} \times w_{eq_k} + w_t \times w_{t_s} + w_v \times w_{v_k}$$

or

$$Cell\ Score = \sum(\sum(w_i \times w_{i_k}))\ for\ all\ i\ in\ the\ cell$$

Similarly, a hazard index for each worker or piece of equipment can be calculated as

$$Hazard\ Index = \frac{\sum(\sum(w_i \times w_{i_k}))}{Total\ observation\ time\ [sec]}$$

6.4 Results and Verification

For demonstration purposes, results from three sets of experiments involving one piece of equipment and one worker is presented. So that the weights can be clarified, the result pertaining to blind spots are shown in the context of a virtual reality model, and the results to proximity are shown in a controlled environment experiment. The three sets of experiments have been carefully chosen with the purposes detailed in their respective description. The algorithm was verified using a virtual environment. This means that if accurate data is obtained, the algorithm is capable of computing the above-mentioned parameters. A controlled environment experiment was used to verify the algorithm in areal world scenario.

i Virtual Reality Model

The purpose of using virtual reality is to obtain ideal data without any instrumental error or external factors affecting the results. For the blind spot, the actual blind spot of the operator needs to be computed considering a volumetric analysis of the operator's head pose, eye position, mirrors, and loading conditions. In virtual reality, an ideal condition without any such effect can be obtained, which is not feasible in the real world. Also, the developed algorithms need to be verified for use in other data sets. The virtual reality model is also used for this purpose because the algorithm can be visually verified by plotting the blind spots of the

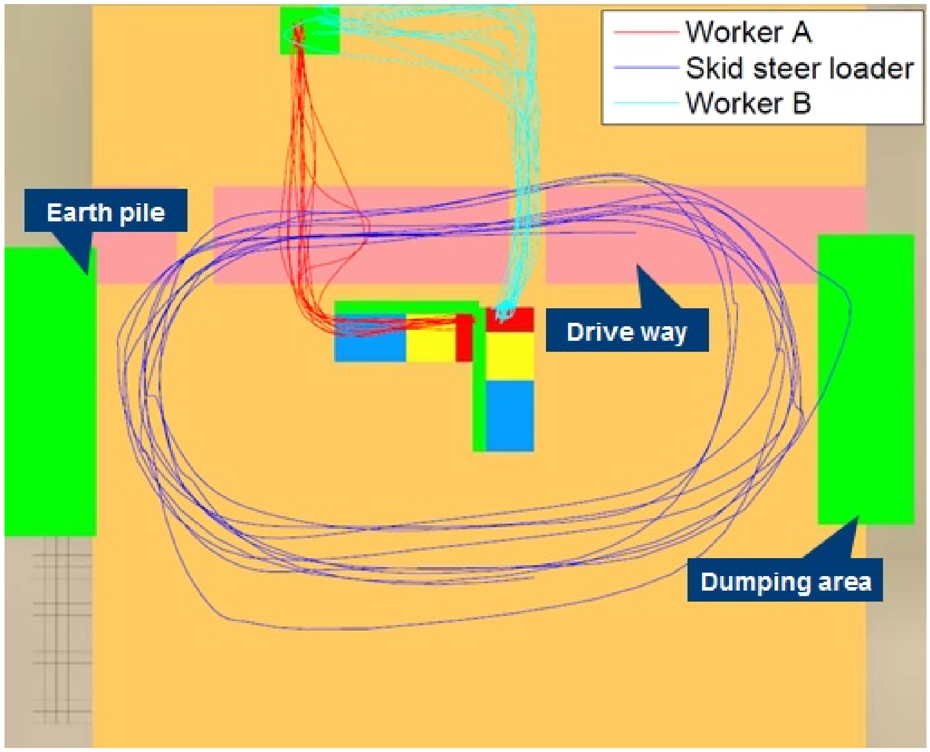


Figure 66: Overview of the virtual reality test environment.

equipment along with the motion of the equipment. Data collection for demonstration is also easier because blind spots, which are not visible on the real site, can be plotted in the virtual world during data collection. Hence, the member acting as a worker knows that he is in the blind spot region even while collecting data. Data pertaining to near miss cases are not practical to be collected on real sites with real equipment. In this case, the use of virtual reality helps because data for any situation can be created without exposing a worker to any real risk.

Figure 66 shows the virtual environment developed in Trimble XYZ software. A skid steer loader that would carry earth from earth pile to dumping area was modeled. Worker A and Worker B frequently cross the path of the skid steer loader on the driveway. The entities in the virtual reality model were moved manually, and data were collected at a frequency of 1Hz.

Figure 67 shows a bird's eye view of the same model. It also shows the blind spot

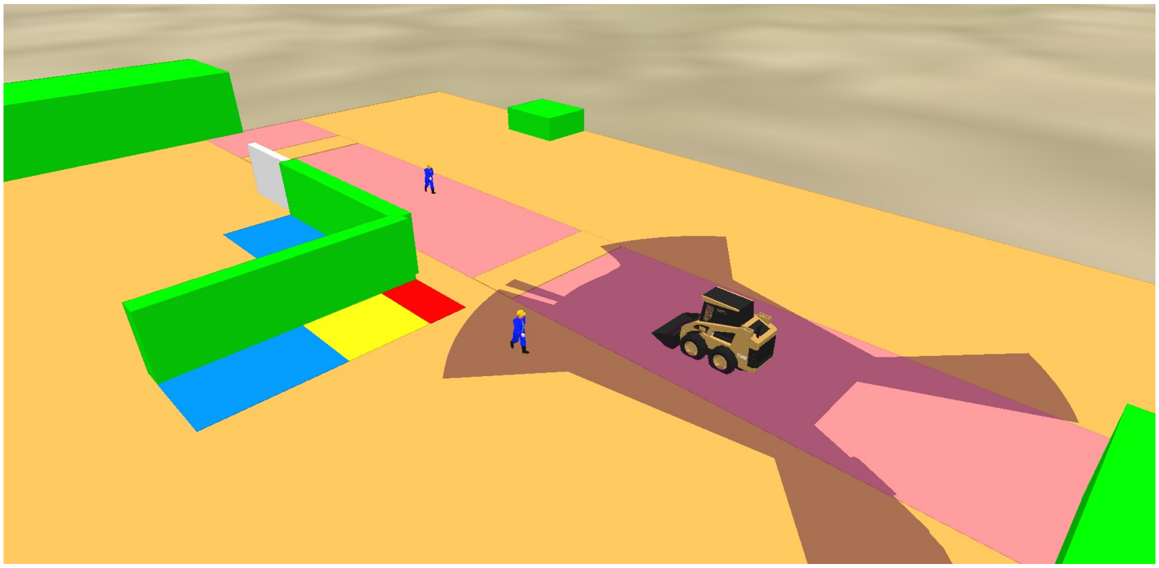


Figure 67: Overview of the virtual reality test environment with equipment blind spot.

of the equipment,which provides a guideline for the workers to understand that they have entered the blind spot of the equipment.

Worker A's trajectory was planned in a way that he/she entered the blind spot of the equipment from every direction. Worker B walked parallel to the equipment and hence entered the blind spot in only one direction. The 3D plot of the trajectories of Worker A and Worker B is shown in Figures 68 and 69. The z-axis represents the time. The figures show that Worker A and Worker B approached the blind spot of the equipment in a cyclical manner in the same area of the site. The trajectory in Figure 66 also suggests the same fact. It is also noted that Worker A was exposed to a blind spot hazard in almost every cycle, while Worker B was less exposed to the blind spots.

This fact can also be visualized on the blind spot map of the equipment to show the potentially most dangerous region of the blind spot map. As mentioned earlier, it is observed that Worker A enters the blind spot from every possible direction while Worker B seems to walk parallel to the equipment thus avoiding more blind

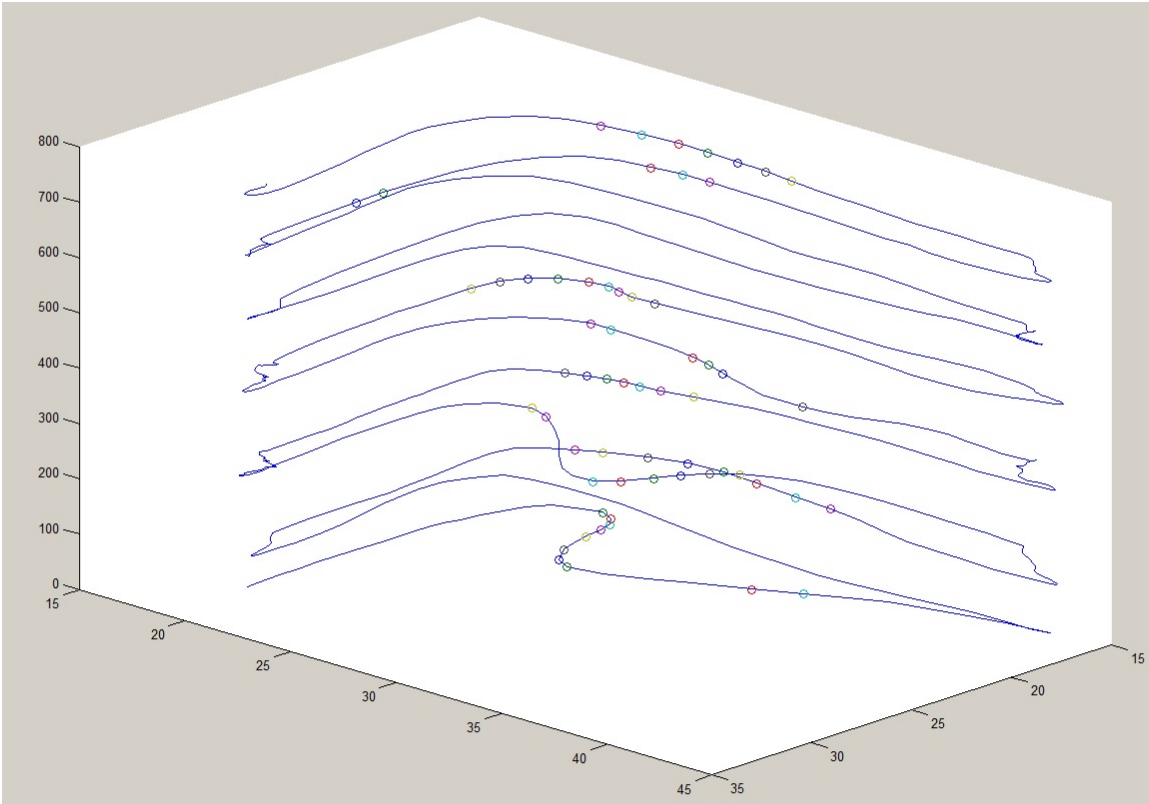


Figure 68: 3D plot of the trajectory of Worker A with blind spot instances.

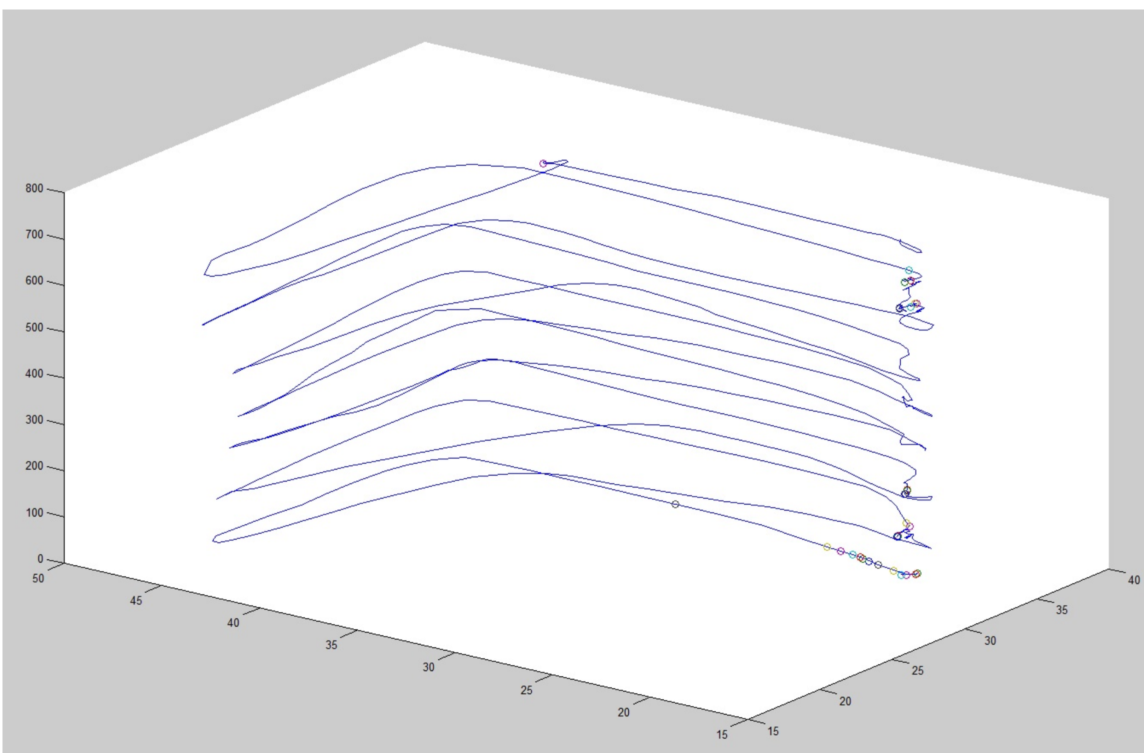


Figure 69: 3D plot of the trajectory of Worker B with blind spot instances.

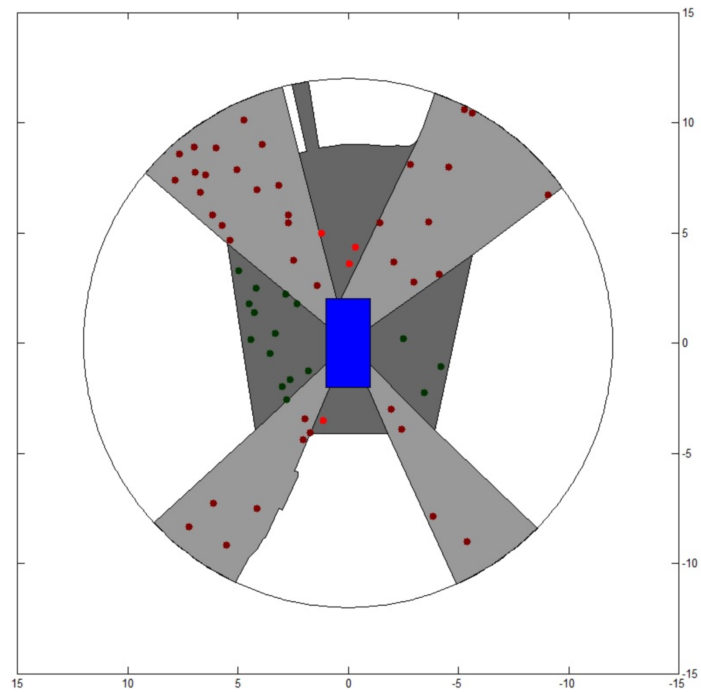


Figure 70: Instances of blind spot entry by Worker A.

spots. This can imply that Worker A needs to be warned about his behavior. In Worker B's case, the equipment operator needs to be aware that most interactions occur on the left side of the trajectory. Such information will increase situational awareness of the equipment operator. The data points in the blind spot regions are color coded to indicate the level of the hazard. Red indicates the most severe cases, while green indicates the least severe cases.

Figure 72 shows a comparison of the hazard index of the workers in a minute by minute basis, making it clear that Worker A exhibited a higher exposure to blind spot risk than Worker B.

ii Controlled Experiment

The second experiment was done in a controlled environment to test if the devices can detect cases of proximity and blind spots in a real world scenario. As mentioned earlier, data collection pertaining to unsafe behavior is not trivial and

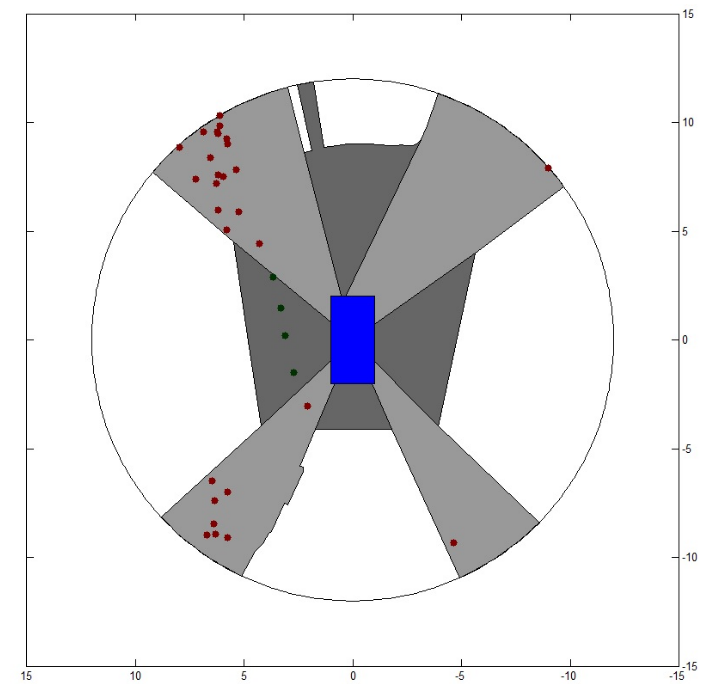


Figure 71: Instances of blind spot entry by Worker B.

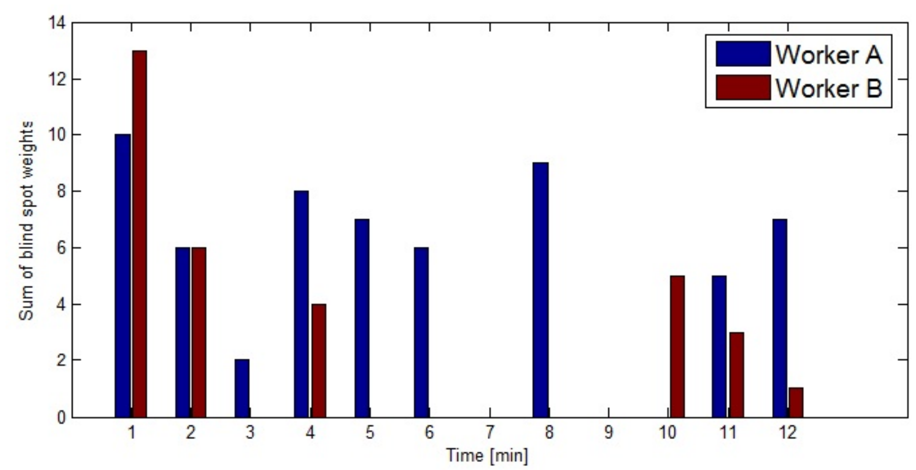


Figure 72: Blind spot hazard index comparison: Worker A vs. Worker B.

Figure 73: Experimental setup.

workers can not be expected to expose themselves to hazards to prove the feasibility of a method. Hence, in the experiment, a test bed was developed, and a passenger car was used to substitute for the construction equipment. Proximity and blind spot conditions were created in a safe environment using real data logging devices.

The roof of the W23 parking lot at Georgia Tech was used as the site for data collection. Figure 73 shows the trajectory of two workers and a vehicle. The blind spot map for the car was obtained from Ray [104].

Figure 74 and Figure 75 show the hazard map for Worker A and Worker B, respectively, based on their proximity to the vehicle. Worker Bs trajectory followed the boundary of the parking lot, whereas Worker A approached the vehicle from all sides.

The direction of approach for the workers is shown in Figure 76 and Figure 77. Worker B was exposed to only one side of the vehicle, while Worker A approached

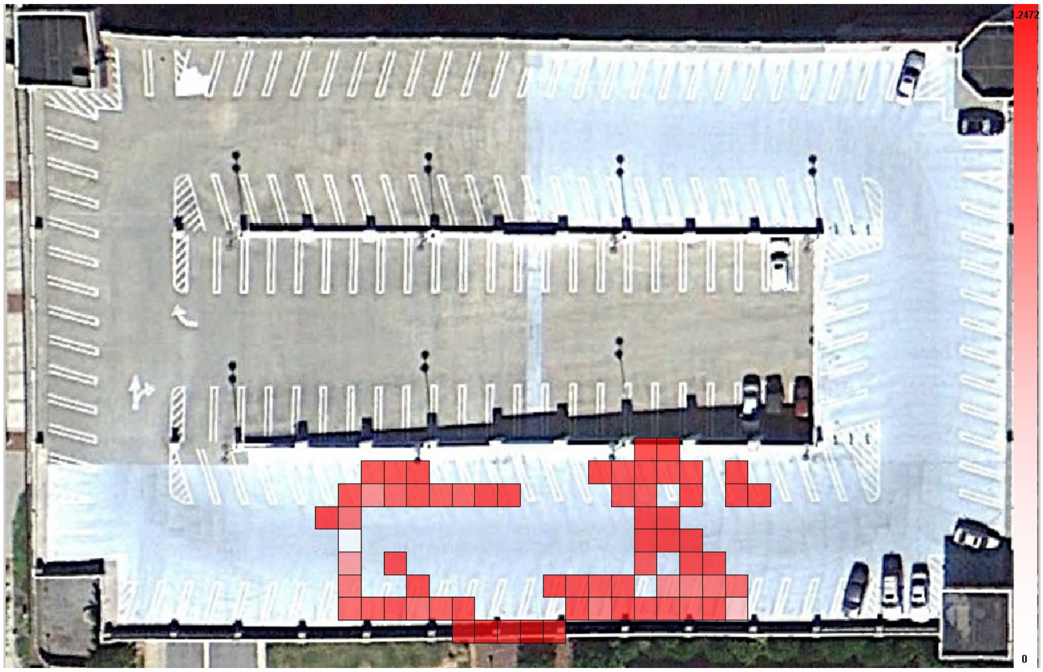


Figure 74: Hazard map for Worker A based on proximity.

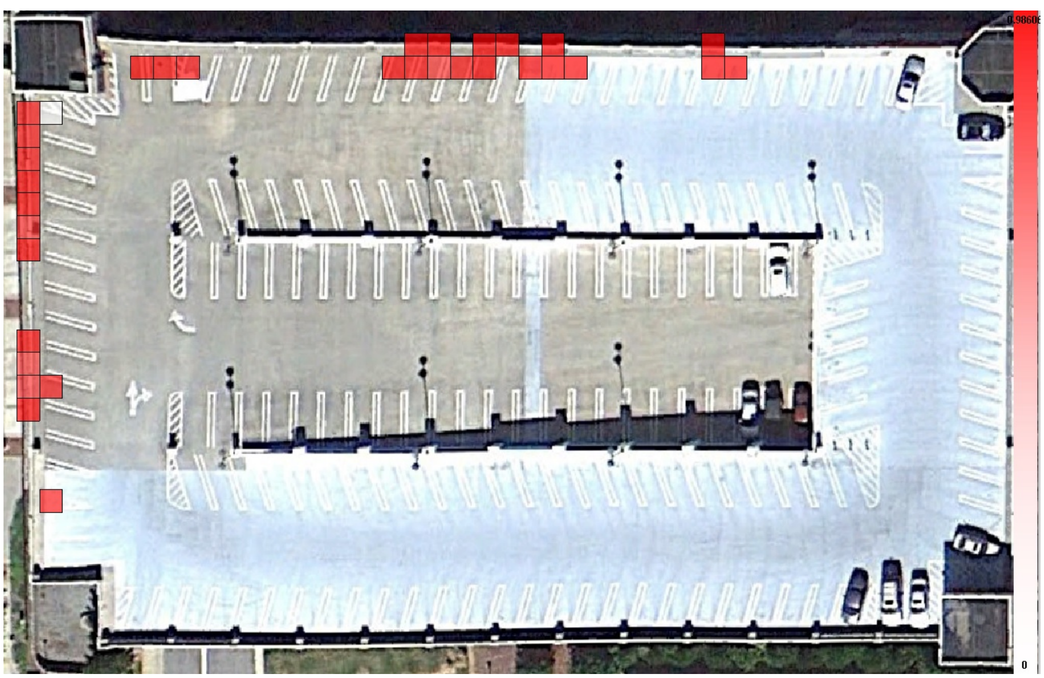


Figure 75: Hazard map for Worker B based on proximity.

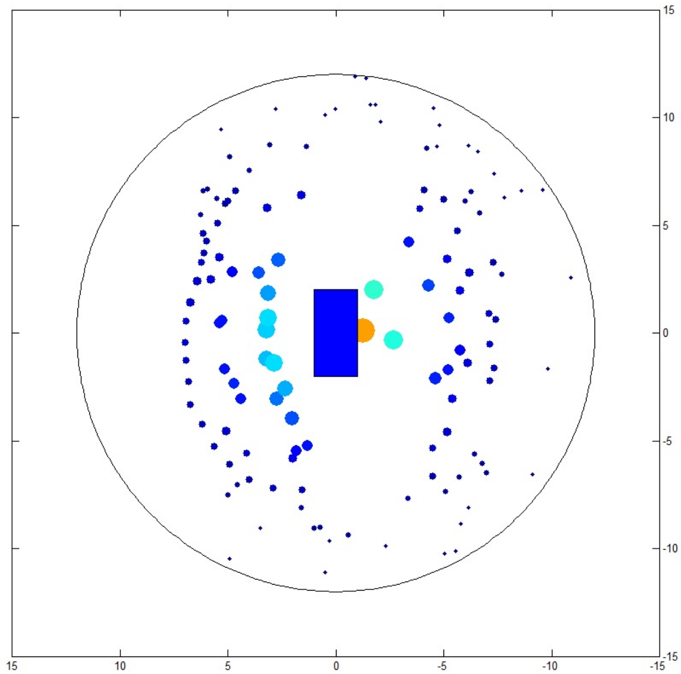


Figure 76: Instances of proximity by Worker A.

close to the vehicle from all directions. The data points are color coded and sized based on their proximity weights. The behavior exhibited by Worker A might lead a collision in future. This information regarding which angle the workers approach the equipment from is equally important for calibrating the proximity sensing devices. The antenna of each device needs to be calibrated based on the region of maximum interference by the workers. Figure 78 shows one of these ranges [82]. Note that the read range is not even around the equipment and that the antennae need to be placed and faced in a proper direction to cover the maximum area possible.

Figure 79 shows the comparison of Worker A and Worker B based on the proximity conditions. As observed from other figures, Worker A was exposed to more potentially hazardous incidents than Worker B.

iii Actual Construction Site

The final step is to test the devices in a harsh construction environment. The

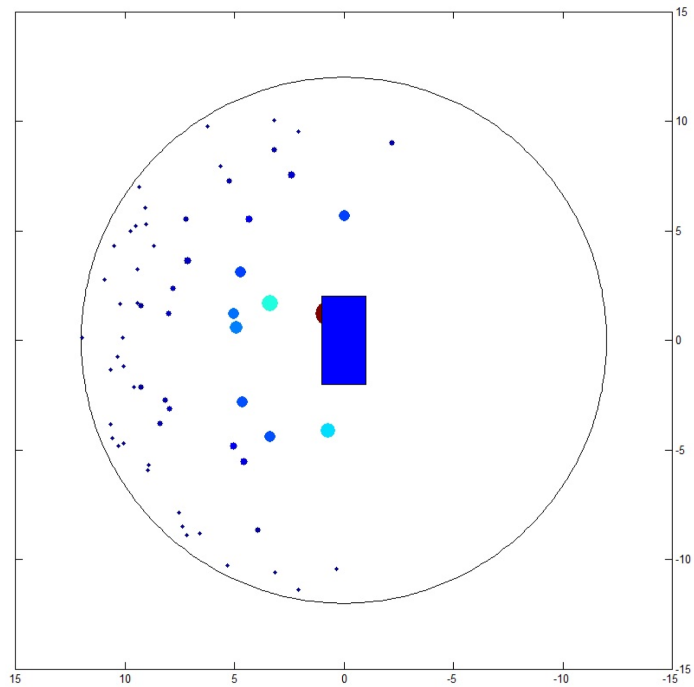


Figure 77: Instances of proximity by Worker B.

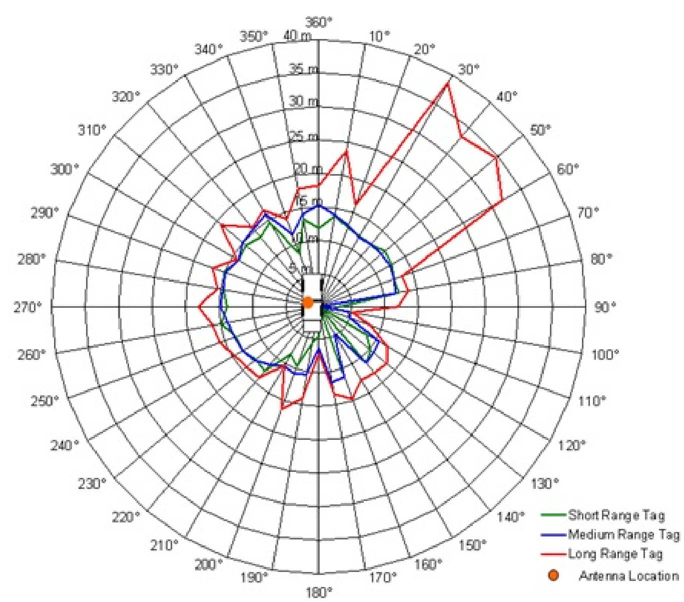


Figure 78: Detection ranges of a proximity sensing device [82].

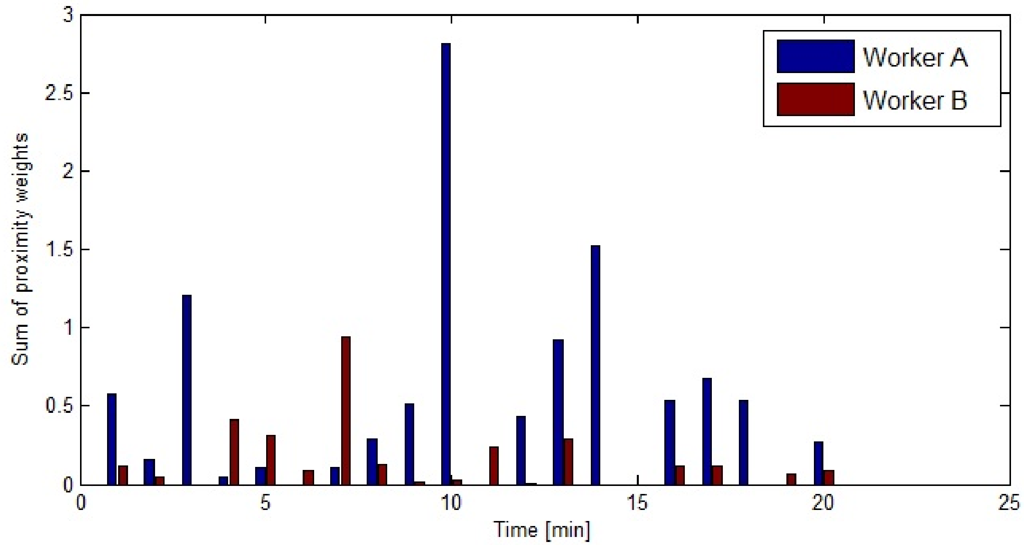


Figure 79: Proximity hazard index comparison: Worker A vs. Worker B.

results of this experiment can not be expected to be as distinct as the results of controlled experiments because safety during data collection is the first concern. The feasibility study was done to demonstrate that the method can be applied and that, in the case that an extremely hazardous condition is present at a site, the method can identify it.

Figure 80 shows the trajectory of a skid steer loader and a person/worker on the ground. Figure 81 shows the trajectory of the worker projected into z-direction by time. The instances when the worker was in the blind spot of the equipment are marked with circles in the plot.

The overall cell scores added together formed a heat map depicting the areas of relative potential hazard on site. Figure 82 shows such a plot.

As discussed previously, the instances of blind spots are plotted in Figure 83. Since the worker and the skid steer loader have to share the same ramp into and out of the pit, the blind spot areas seem to be densely cluttered.

Figure 84 shows proximty region map plotted for a radius of 12 m around the skid steer loader in. Similar to a blind spot, the proximity region is also densely

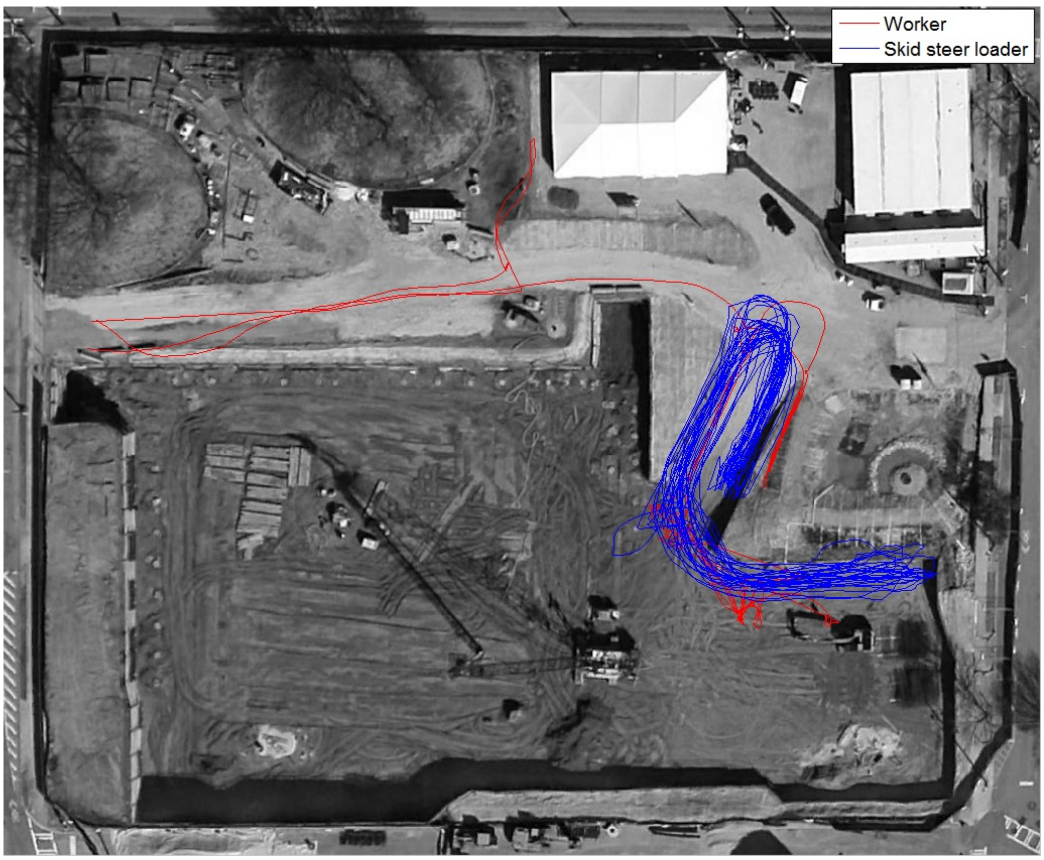


Figure 80: Overview of the site.

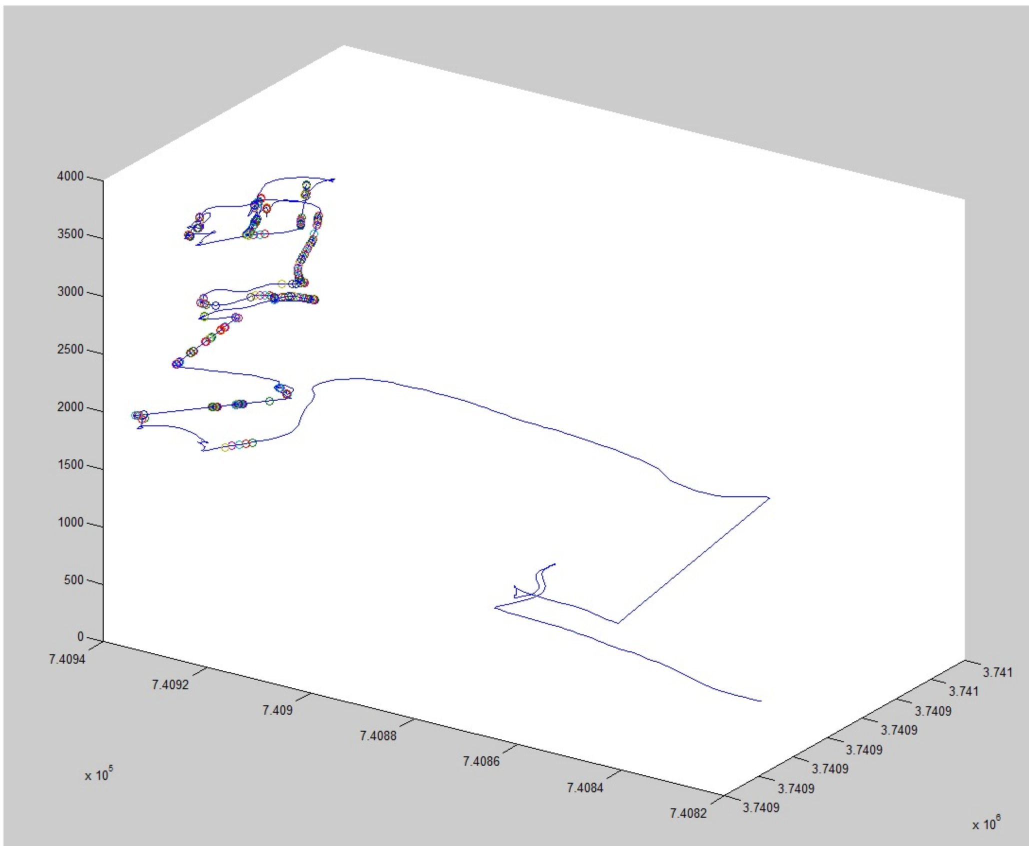


Figure 81: 3D plot of the worker's trajectory.

Figure 82: Heat map for overall cell score.

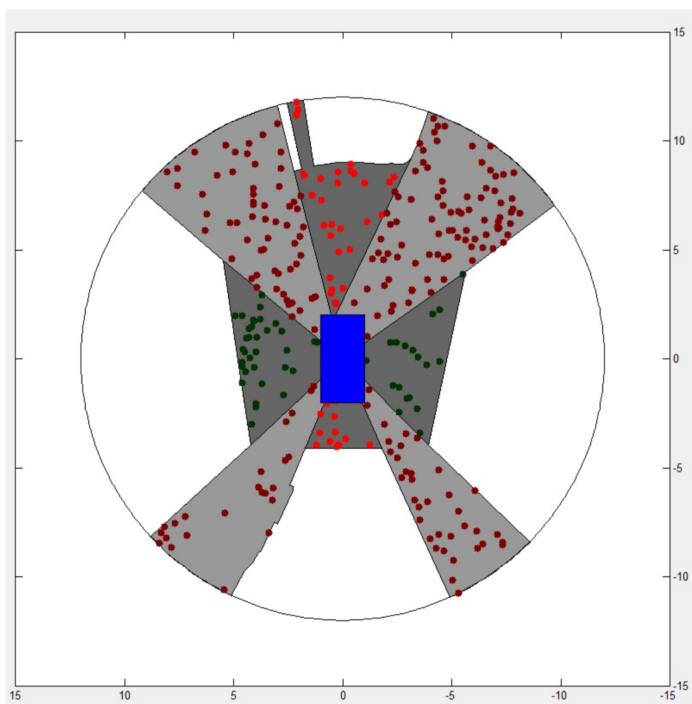


Figure 83: Instance of the worker in blind spot region.

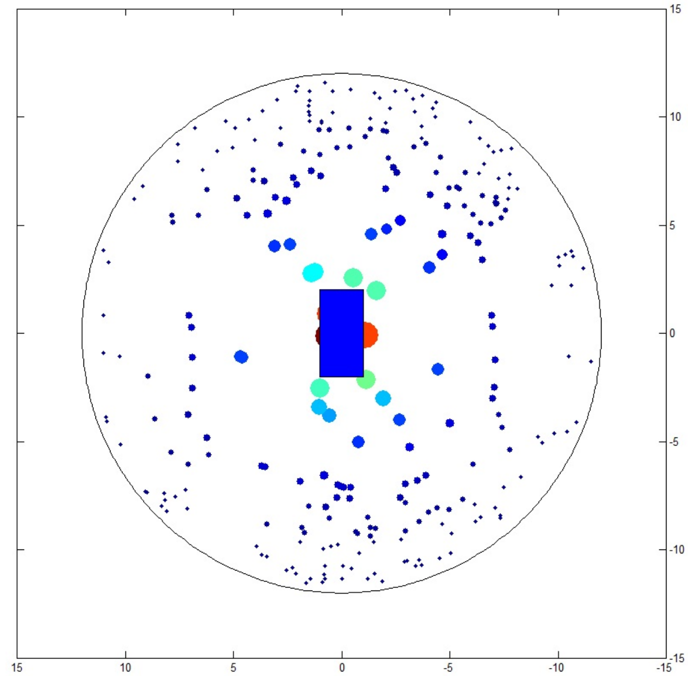


Figure 84: Instance of the worker in proximity region.

cluttered. Some data points seem to be plotted inside the equipment. This can be attributed to instrumental error.

The hazard index chart is plotted for each minute of the worker's trajectory. Figure 85 shows the absence of any value until the worker approaches the pit, where he/she then had a major interaction with the skid steer loader.

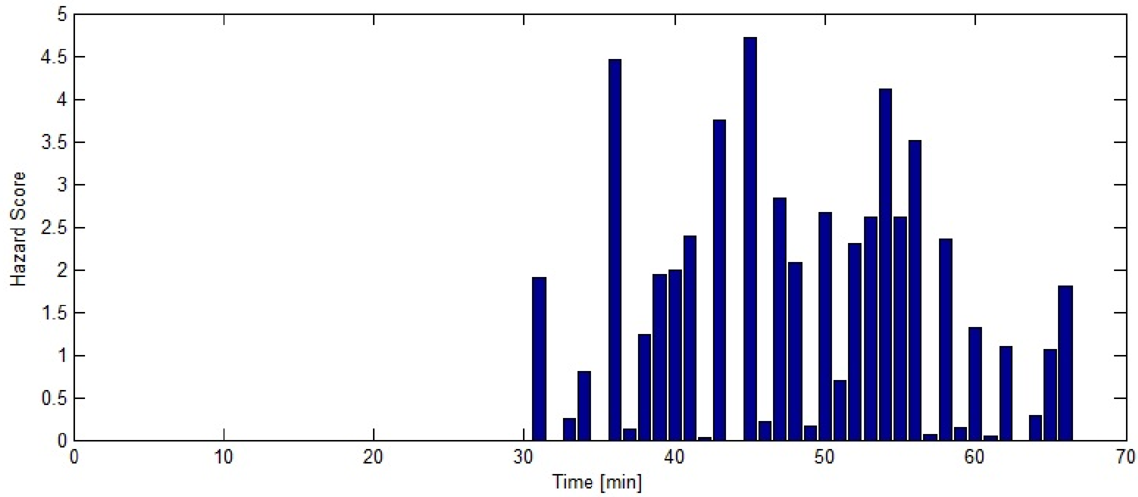


Figure 85: Hazard Index distribution of the worker.

6.5 Summary

Chapter 6 presents a method of collecting information regarding the at-risk behavior of the workers interacting with equipment. This method can be used to better understand the safety situation at a site and to identify the areas of potential hazard inside the site. This method will help safety managers focus on the areas that require more attention based on statistical data and the motion behavior of the resources. The spatio-temporal parameters that can potentially cause hazards are identified, and a weight-based approach is developed to rank the parameters based upon their severity. Resources (workers or equipment operators) exhibiting at-risk behavior can be identified and any need for training or warning can be determined. Data from a virtual reality environment, a controlled experiment, and real construction site were used to test the applicability of the method. The method needs to be validated by collecting actual data from the site. The potential issues identified by this method should be compared to safety or near-miss incidents reported at the site and by manual observation by safety experts. This process of validation should be performed in multiple site conditions with varying resource configurations. This research only verifies the developed algorithms but does not validate the results against actual site safety conditions at site.

CHAPTER VII

CONCLUSIONS AND RECOMMENDATIONS

This chapter presents the concluding remarks, highlights the contributions of this research, and discusses the limitations of the current research as well as future research needs.

7.1 Summary of Analytical Work

This research devised a consistent and reliable method of analyzing spatio-temporal data for construction site safety analysis compared to manual observation methods. This research demonstrated that sensing technology can be deployed in the field to gather valuable information about the at-risk behavior of the workers and equipment operators. Implementation of this method in the field will enable safety managers to objectively identify the areas requiring attention and assist them in minimizing or eliminating undesired incidents on a construction site. Unlike manual observation methods, which depend upon random sampling of observations, this method encourages continuous monitoring, which can be less labor intensive, more effective, and less subjective.

This research started out with testing the reliability of the adapted low cost GPS technology in the field and made recommendations regarding what types of interactions can be analyzed using the technology. From a technological perspective, tracking workers on a construction site to study human-equipment interaction opens a new door to understanding the site in detail and performing high resolution analysis of the causation of hazards.

The automatic operation analysis platform provided a solid ground for the managers to keep track of activities occurring at the site. Before making future plans or inspecting for safety, managers must have knowledge of the site operations in detail. Based on this knowledge, they can make effective and timely decisions for resource optimization, site safety planning, and internal traffic control plans. Zone and speed analysis enables consistent record keeping of the time distribution of resources in their work zones. Analysis of cyclic activities assisted not only in keeping track of movements inside the site but also provided real data from the site for use in the simulation model. The method of feeding real data from the site will result in a more realistic simulation model that even more closely represents the site. If spatial constraints are taken into consideration, the cell-based simulation model simplifies the simulation process. The effect of changing the number of resources in the site on site occupancy was simulated and visualized for better understanding.

The parameters that affect safety conditions inside a construction site were identified, and a way to quantify them was presented in the hazard mapping section. The developed hazard analysis method focused on a statistical base for quantifying potential hazards. For those parameters without guidelines for safe operation, appropriate weighing functions were assigned. The entire method worked on model formation based on past injuries and near-misses. Even in the case of wrong weights assigned to the parameters, the weights improve over time to fit the real-site situations.

7.2 Contributions

The core contributions of this research can be summarized as below.

- Automated and sophisticated construction operation analysis platform using continuous spatio-temporal data
- Cell-based construction operation simulation engine for continuous simulation of resource interaction in a spatially constrained environment
- Identification, quantification, and reporting of potential hazards for improved

situation awareness of workers, equipment operators, and safety managers

- Method of assessment of safety plans by objective comparison among alternatives

The framework consists of parts that contribute individually to their respective fields. The overall framework builds a novel method that utilizes real-time data from the site to understand the operations occurring at the site, to predict the effect of changing the site resource configuration on resource interaction, and to analyze potential hazards on site automatically to assist safety managers in monitoring, controlling and planning. Each module opens a path to explore new opportunities by making data driven decisions for construction safety monitoring and planning instead of relying on manual observations and personal experience. Decisions based on actual real-time data from the site have the potential to save lives and develop an overall safer work culture at construction sites.

7.3 Limitations

The research presents a data collection and analysis model. The analysis is not done in real-time. It is important to understand the behavior of the workers, since sensing technologies can alert workers as soon as such behavior is identified. This research proposes a pro-active method for safety management, but it is suitable only for planning (short term and long term) and is not applicable for on-site detection of hazards.

The technology used in this research works only in outdoor environments, and the data needs to be downloaded at the end of every day. The accuracy of the devices was found to be questionable for critical aspects like safety. Development of sensing technologies has been taking place exponentially. This development is improving the accuracy significantly. It has enabled real-time transmission of data and cloud based analysis for just-in-time alerts. Other technologies capable of gathering data from the resources should be investigated.

The research deals only with spatio-temporal aspects of resource interaction. Other factors such as environmental factors and human behavior play a vital role in the causation of hazards. Such factors should also be incorporated in the analysis process. Types of hazards other than human-equipment interactions have not been studied . There might be a potential for analyzing some of these interactions using spatio-temporal data. Such exploration needs to be done.

The operation analysis platform is dependent upon the user for information regarding work zones, start and end zones of cycles, and resources involved in such activities. Manual input of such information can be tedious, especially when the site is busy. Automatic extraction of such information from the project schedule of BIM needs to be developed. Zones can also be automatically detected based on the motion behavior of the equipment and workers. Algorithm development for such detection will save a lot of effort for management.

Cell-based simulation is computationally expensive compared to discrete event simulation. Because the trajectory of the resources was the main interest in the research, a compromise was done with computational need. An optimized method yielding both economy in computation and consideration of space needs to be investigated.

The output obtained from the developed algorithms have been verified. That means the algorithms have been tested to yield the expected outcomes. But the relevance of the output to actual site conditions have not been validated. Validation is the process of comparing the results from the algorithms to actual observations from the site. Validation need to be done by collecting data from multiple construction sites with different resource configurations. If the ground truth or actual site observations cannot be easily obtained, a manual video analysis by experts can be used for validation. Operation analysis and simulation modules can be validated by collecting more data from the site and comparing the results with actual observations from the site. For potential hazard identification and analysis module, the results should be compared with safety and near-miss issues reported at the site or by manual analysis of video by safety experts. This validation process needs to be performed for each hazard weighing parameters separately as well as in combination (composite parameters). This research deals with development of the framework and verification of the method. Further experiments need to be done to validate the method.

7.4 Future Works

The research framework utilizes data from the site and historical statistics or knowledge about safety for potential hazard analysis. Figure 86 shows the flowchart of data among different components of the framework. Data pertaining to site geometry is fused with real-time data from resources to understanding the safety conditions at site. Each instance at site is recorded and compared with site and resource safety statistics.

Statistics regarding the safety conditions are not only utilized but also continuously generated in every instance. The results from hazard analysis can be utilized to update the existing statistics and tune up to accurately reflect the site condition. A digital copy of the entire site, which is created at each instance, can be used to extract only the relevant statistics from historical observations. For example, instead of relying upon the entire data set of fatalities for applying weights, managers can extract historical conditions similar to present site in terms of the quantity of equipment, the operations being performed, and the size of work. The situations in which undesired events occurred in past can be marked, and preceding time frames that led to such situations can be analyzed.

The framework will serve not only as a hazard analysis platform but also as a

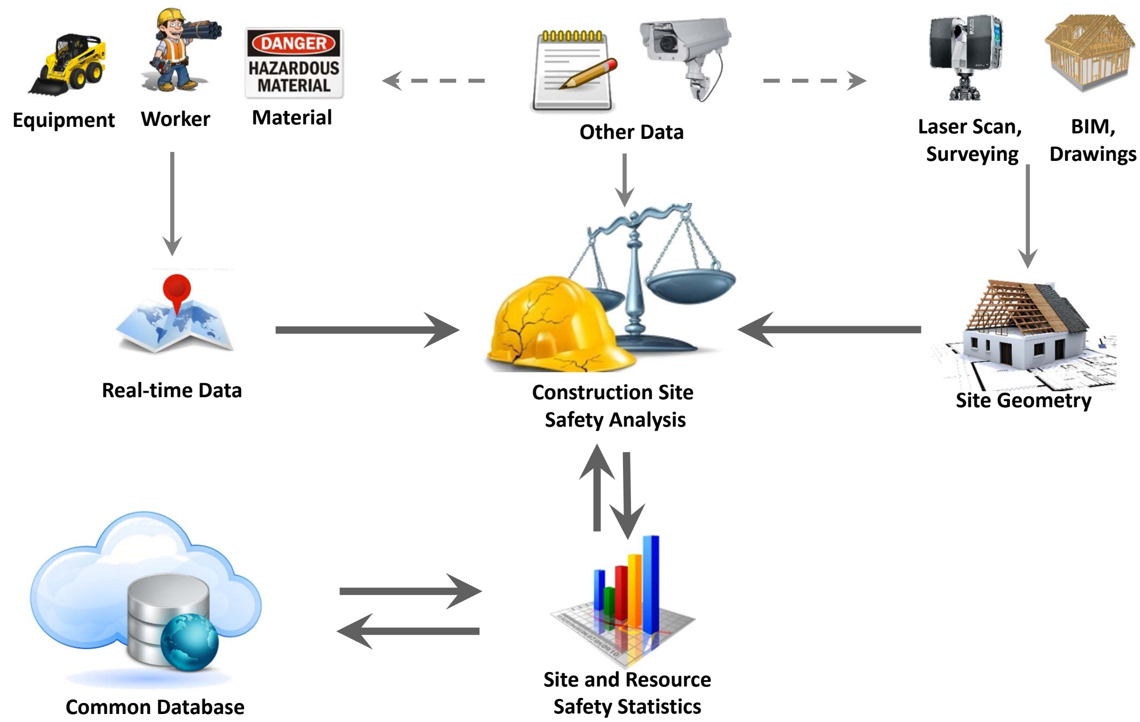


Figure 86: Outlook for the research framework.

repository of all the unsafe events that happened in the past. Information generated from hazard analysis can be stored in a database that can be retrieved for future hazard analysis. This repository of results of hazard analyses can be shared among different projects in the company or even among different companies to learn from each other. A repository of this kind can also have a role in productivity analysis.

The framework can readily incorporate developments in the fields of the weighing parameters. For example, the blind spot map used for equipment in this research is a static map. A dynamic blind spot map that adjusts its shape based on the operator's head and eye orientation can be directly incorporated into the framework. The analysis is done independently in each instance, so the blind spot can be updated in each instance to reflect the actual blind spot on site. Similarly, the effect of mirrors, boom locations, and weight etc. can also be easily accommodated in the same was as blind spot mapping methods advance. Volumetric blind spots can also be utilized instead of a two dimensional map if the technology allows.

The framework can also be extended for other types of real-time data from the site such as temperature, humidity, body posture, education level, age of workers, size of company and type of work, and material being handled. Beyond real-time data, parameters that affect the safety conditions,for example, managerial practices and human behavior, can also be accommodated to create a robust hazard model in the site.

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VITA

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